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Industrial Radiography
on
Radiographic Paper

by

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Abstract

An investigation was performed to compare the quality of radiographic paper with that of X-ray film, after a review had been made of the rather scarce literature on the subject. The equipment used throughout the investigation is described, and characteristic curves for Agfa-Gevaert and Kodak papers exposed with different intensifying screens in the low and intermediate voltage range are reproduced. The relative speed, contrast and exposure latitude were computed from these curves. The quality of the radiographic image was checked on U/Al blocks and plates, Al and Fe blocks, and fiber-reinforced composites. Exposure charts for Al and Fe were made for various paper and screen combinations. Both the sharpness of the radiographic image as well as the influence of processing on speed and contrast were checked. Examples are given of the practical application of the paper for radiography of castings, weldings, solderings, assemblies, etc.

*) Work performed under contract with Risø National Laboratory

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1. INTRODUCTION

To anyone performing quality control of numerous similar items, the possibility of using a cheaper and faster control method must be attractive. Such was the case with our quality control of MTR fuel elements, during which a large quantity of cast blocks and rolled plates have to be controlled by radiography. This was previously carried out on X-ray films that are comparatively expensive and require a rather long processing time. Therefore, the possibility of using X-ray paper (which is not only three times cheaper than X-ray film but can also be processed in about 10 s) immediately attracted our attention as soon as it became commercially available (together with suitable processing machines).

Before taking the decision to replace X-ray film by X-ray paper, one must be sure that the quality of the radiographic image will be maintained. Therefore, an investigation was performed to compare the quality of paper radiographs with that of film radiographs.

Before performing the investigation, a literature search was made on the application of X-ray paper to industrial radiography. It was surprising how little had been published on this technique that has been known for the last decade. Only very few publications could be found from before 1971 when Kodak put their Industrex 600 paper (and a suitable processing machine) on the market[1,2,3,4].

Even after this date very scant attention was paid to the new radiographic tool. Looking through the radiographic literature, one can find very few reports on serious and extensive investigations of the use of radiographic paper[5,6,7,8,9,10,11].

The information provided by the X-ray paper manufacturers is also scarce, and much poorer than that for the X-ray films.

Hence it seems that many workers in the field of radiographic quality control must be unaware of the intrinsic merits of paper radiography.

2. RESULTS OF THE LITERATURE SEARCH

As mentioned before, there have been only few investigations on the sensitometric properties of radiographic paper, and the data available from its manufacturers are also scarce.

2.1. Investigations of the properties of radiographic paper

Before 1971 when Kodak put its Industrex Instant Paper on the market[4], several kinds of photographic paper were investigated with a view to radiography applications. As early as 1960, Couchman[1] reported on the possibilities of using bromide paper for radiography. In 2) and 3) results of such an investigation performed on direct print recording oscillograph paper are given. J.C. Rockley reported[5] on two types of photographic paper marketed in Great Britain specifically for industrial radiography, but he did not mention either the name of these brands or their manufacturers. He investigated these two brands with a developer-incorporated paper (matt finish), a bromide printing paper (high contrast, glossy) and a developer-incorporated paper (high contrast, glossy). All were compared with X-ray film, non-screen, fine grain, high contrast.

Another paper by Rockley[6] reports on the results obtained during the investigation of photo-stabilisation paper (photographic printing paper incorporating a developing agent in the emulsion). Although the author does not mention the brand of paper investigated, LR Ilfoprint projection paper is mentioned on the sensitometric curves.

A short report was published in Metal Progress in 1973[7] on the application of Kodak Industrex Instant 600 paper used with an F2 Industrex intensifying screen. Mention was also made of the possibilities of using the 600 paper for neutron radiography[8].

The same brand of Kodak paper was also used in the investigation[9] during which steel was radiographed with 150, 200 and 300 kV X-rays as well as Co-60 gamma-rays.

A well known German handbook on NDT[10] only gives a very short, superficial description of radiographic paper without mentioning any particular brand.

Before introducing radiographic paper at Risø for the quality control of MTR fuel elements, an investigation was made to compare the quality of radiographs obtained on Kodak Industrex Instant 610 and Agfa-Gevaert Structurix IC paper with those obtained on X-ray films[12]. At the time of this investigation only the Kodak 610 paper (manufactured by Kodak-Pahté in France) was available.

On the occasion of the Eighth World Conference on Nondestructive Testing (6-11 September 1976, Cannes, France) Kodak-Pathé issued a special publication: "Applications scientifique et industrielles de la photographie" in which P.A. Ruault described his investigation of the application of radiographic paper to the control of weldings[13]. The comparison of the Kodak 600 and 610 papers, used with different kinds of intensifying screens, and X-ray films, was made using a constant exposure (mAmin) technique, which was described by Ruault[14] at the 8th WCNDT.

Both 13) and 14) mention different types of fluorescent intensifying screens (such as D1, R4, R7, U2, MR400, MR600, G359) and fluorometallic screens (FM) used with the radiographic paper, but no details are given of the characteristics or the manufacturers of these screens.

It is indicated in 13) that, using the same intensifying screen, the Kodak Industrex Instant 600 paper shows a speed about twice as fast as that of the 610 paper. In the investigation described in 14) only the 600 paper was used. The most extensive research done on the sensitometric properties of radiographic paper is reported in 11) by Holloway. It was later published in condensed form in 15).

Kodak 600 paper was tested with Kodak fluorescent F-1 and F-2 intensifying screens. Characteristic curves and exposure charts for aluminium were produced up to 90 mm at 25 to 150 kV. IQI sensitivity was also investigated using the MIL-Standard 453 penetrameters. It was proved that the Instant 600 paper with the F-1 screen is capable of 2 per cent penetrameter sensitivity with aluminium. As a result of this investigation the US Air Force Logistics Command purchased over 100 paper processors for use by nondestructive inspection groups throughout the Air Force.

2.2. Information supplied by paper manufacturers

In practice, there are only two X-ray film manufacturers offering systems for paper radiography. The Kodak system consists of the Industrex Instant paper (made in USA by Eastman Kodak Company as Instant 600 paper and in France by Kodak-Pathé as Instant 610 paper). For both paper brands, Industrex Instant

Processor Model P 1 is used with Industrex Instant Activator and Industrex Instant Stabilizer. The 600 paper is available in 13" x 17" (35.6 x 43.2 cm), 8" x 10" (20.3 x 25.4 cm), 4½" x 17" (11.4 x 43.2 cm) sheets and in 70 mm x 152.4 m rolls. The 610 paper can be obtained in 13 x 18, 18 x 24, 24 x 30 and 30 x 40 cm sheets.

Fluorescent intensifying screens of the F-1 and F-2 types are available from the Eastman Kodak Company for paper radiography (recently an X-omatic Regular Screen has been introduced as equivalent to the F-1 type).

The Agfa-Gevaert IC system consists of the Structurix IC paper (available in sheets of the following dimensions: 13 x 18, 18 x 24, 24 x 30, 30 x 40, 10 x 48, 50 x 60 cm and 4½" x 17", 8" x 10", 14" x 17"), the Structurix IC fluorescent screens Type II (same dimensions as the paper), two types of processing units - Structurix IC35 (maximum paper width 37 cm) or Structurix IC50 (maximum paper width 54 cm), in which Activator G 126 and Stabilizer G 326 are used.

The information given by the manufacturers on the sensitometric properties of their products is very scarce and incomplete.

2.3. Relative speed

Kodak-Pathé[16)] gives two sets of characteristic curves for its 610 paper, exposed with high speed, standard and high definition intensifying screens at 120 kV through 1 mm of copper. For the sake of comparison, a characteristic curve is given for the Industrex A X-ray film (exposed without screens under the same conditions) (see fig. 1). Paper and film speeds were compared at densities $D_f = 2$ (above base and fog density) for the X-ray film and $D_p = 0.6$ (above base and fog density) for paper. The relative speeds are:

Table 1

Relative speed of Kodak Instant 610 paper exposed at 120 kV through 1 mm of Cu[16]

Film Industrex A No-screens	Paper Instant 610 with intensifying screens		
	High definition	Standard	High speed
	1.3	5.4	7.5

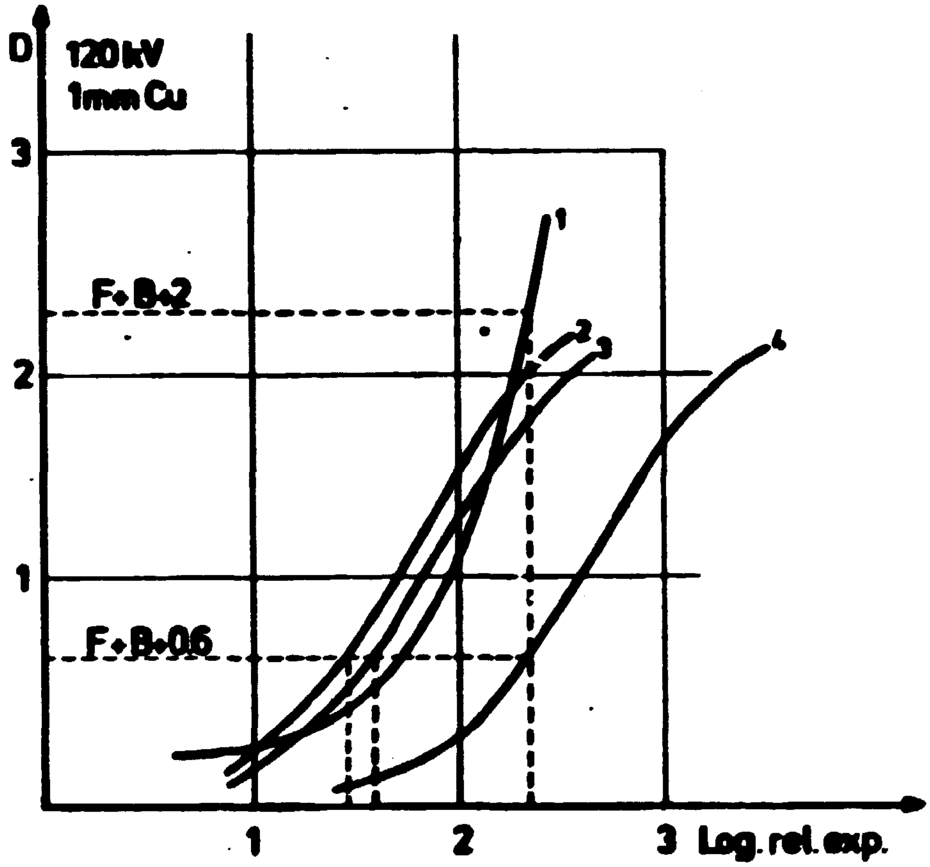

Fig. 1. Characteristic curves of the Kodak Instant 610 paper and Industrex A film at 120 kV (exposed through 1 mm of Cu)[16]

1 - Film Industrex A - no screens

2 - Paper 610 - high speed screen

3 - Paper 610 - standard screen

4 - Paper 610 - high definition screen

F + B - fog and base density

A less complete comparison is given for a 250 kV exposure through 10 mm of copper. Here the Instant 610 paper with high speed screen is compared with the Industrex A film exposed without screens and as a lead pack (see fig. 2). Relative speeds (calculated as in table 1) are given below:

Table 2

Relative speed of Kodak Instant 610 paper exposed at 250 kV through 10 mm of Cu[16)]

Film Industrex A		Paper Instant 610 with high speed intensifying screens
No-screens	Lead pack	
1	2.8	12

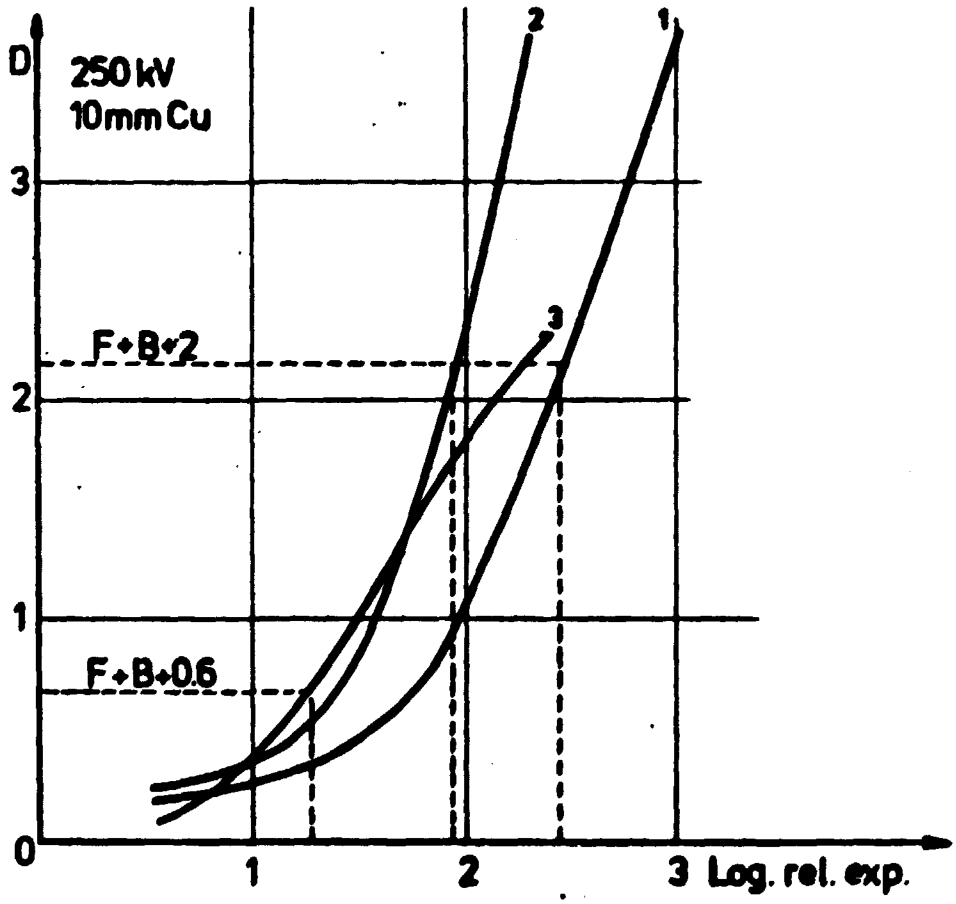

Fig. 2. Characteristic curves of the Kodak Instant 610 paper and Industrex A film at 250 kV (exposed through 10 mm of Cu)[16)]

1 - Film Industrex A
2 - Film Industrex A - lead pack
3 - Paper 610 - high speed screen
F + B - fog and base density

Quite different results were obtained by Ruault[13] who compared the 610 paper with Industrex A film, also at 120 kV (as on fig. 1 and in table 1), but exposed through 5 or 10 mm of steel. Table 3 gives the results published in 13).

Table 3

Relative speed of Kodak Instant 610 paper exposed at 120 kVcp through 5 or 10 mm of Fe[13]

Film Industrex A 0.05 + 0.20 mm Pb screen	Paper Instant 610 with intensifying screens exposed through 5 or 10 mm of Fe									
	R 7		R 4		FM		U 2		D 1	
	5	10	5	10	5	10	5	10	5	10
	mm Fe		mm Fe		mm Fe		mm Fe		mm Fe	
1	12.5	10	6.7	7.1	4.3	4.8	3.0	2.9	2.3	1.8

Unfortunately, neither the Kodak-Pathé pamphlet 16) nor the 13) paper give any exact information about the type and manufacturer of intensifying screens used with the 610 paper. It must be further observed that the comparison criteria applied by Kodak-Pathé and Ruault were different: Kodak compares the speed of the X-ray film at $D_f = 2$ with that of the 610 paper at $D_p = 0.6$, whereas the respective densities used in 13) are $D_f = 1.5$ and $D_p = 0.6$

The information that could be found about the Kodak Industrex Instant 600 paper is even less complete. The Eastman Kodak pamphlet[17] states that the 600 paper is approximately 6 times faster than the Industrex AA film exposed with lead screens at 140 kV when used with F-1 screens, and 1.5 times faster when used with F-2 screens. With direct exposure, the 600 paper has approximately the same speed as Industrex M film.

Quite different values are quoted in 15). The authors exposed the 600 paper without and with F-1 and F-2 screens at 75 kV through 25 mm of Al and compared speeds from characteristic curves obtained at 1.2 m FFD (see fig. 3) with that of ready pack Industrex AA film (comparison was made at $D_f = 2.0$ for film and $D_p = 0.75$ for paper). Comparative speeds found from fig. 3 and stated by Eastman Kodak are given below.

Table 4

Relative speed of Kodak Instant 600 paper exposed at 75 kVcp through 25 mm of Al[15)]

Film Industrex AA ready pack	Paper Instant 600 and intensifying screens					
	without screens		F-1		F-2	
	/15/	Kodak	/15/	Kodak	/15/	Kodak
1	0.56	0.50	13.7	11.0	2.8	1.3

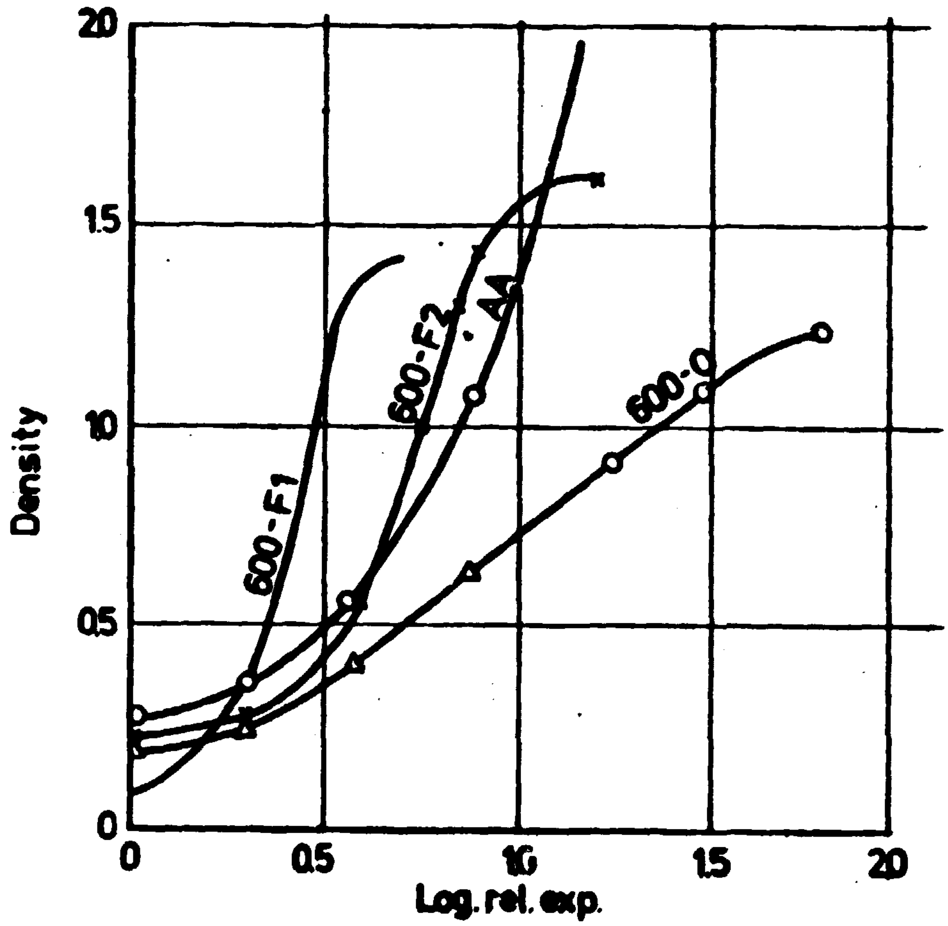

Fig. 3. Characteristic curves of Kodak Instant 600 paper and Industrex AA film[15)].

Ruault[13] published similar results for the 600 paper as quoted in table 3 for the 610. They are given below:

Table 5

Relative speed of Kodak Instant 600 paper exposed at 120 kVcp through 5 or 10 mm of Fe[13]

Film Industrex A 0.05+0.20 mm Pb screens	Paper Instant 600 with intensifying screens exposed through 5 or 10 mm of Fe													
	No screens		R 7		R 4		F M		U 2		D 1		6359	
	5	10	5	10	5	10	5	10	5	10	5	10	5	10
	mm Fe		mm Fe		mm Fe		mm Fe		mm Fe		mm Fe		mm Fe	
1	0.37	0.13	25	20	12.5	12.5	11.1	9.1	6.25	5.25	4.0	1.82	33.3	

Nothing could be found in the literature on an investigation of the Agfa-Gevaert IC System. Therefore an investigation was performed at Risø before using the radiographic paper for the quality control of MTR fuel[12]. Here the IC paper with IC Type II screens was compared with the 610 paper with X-omatic screens.

Some description of the sensitometric properties of the IC System is given in the Agfa-Gevaert pamphlet[18]. Characteristic curves are given for the IC paper exposed without and with lead and IC II intensifying screens together with a curve for the D7 film with lead screen (thickness not specified) (see fig. 4). No speed values are quoted in 18), but a comparison (from fig.4) of the exposures necessary to obtain a film density of $D_f = 2.5$ with those necessary to obtain paper densities of $D_p = 1.0$, gives the following values of relative speed:

Table 6

Relative speed of Agfa-Gevaert Structurix IC paper (calculated from curves in 18)

Film D7 lead screens	Paper IC with intensifying screens		
	No screens	Lead screens	IC Type II
1	0.6	1.5	15

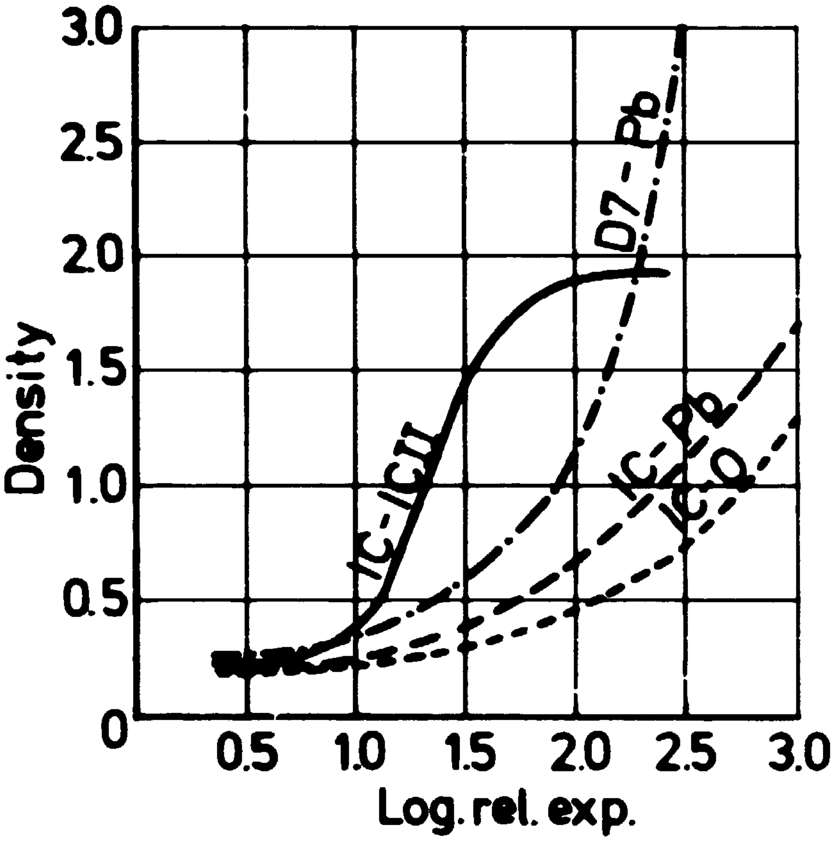

Fig. 4. Characteristic curves of Agfa-Gevaert Structurix IC paper and Structurix D7 film[18].

2.4. Gradient and exposure latitude

The density gradients of the characteristic curves of the Kodak Instant 600 paper were measured[15] for the AA film (in the density region from 1.65 to 2.02) and for the 600 paper (in the density region from 0.7 to 0.8). The results are given below (exposure conditions as for fig. 1).

Table 7

Gradients of AA film and 600 paper[15)]

Film AA		Paper 600 with intensifying screens					
Density range	Gradient	No screens		F 1		F 2	
		Density range	Gradient	Density range	Gradient	Density range	Gradient
1.65-2.02	3.7	0.7-0.8	0.8	0.7-0.8	4.0	0.7-0.8	2.8

Ruault[13)] determined the contrast (density gradient) of the 600 and 610 paper from density-thickness charts used for the production of exposure charts. It was found that the 600 paper has a better contrast than the 610. In the density range of $D_p = 0.7 \pm 0.3$, a difference of 1 mm Fe gave a density difference of 0.4 for the 600 and of only 0.2 for the 610 paper. These measurements were made at 120 kVcp using R7 intensifying screens. The latitude was investigated[15)], and the results for the 600 paper obtained from the characteristic curves are quoted below:

Table 8

Exposure latitude for AA film and 600 paper for Al[15)]

Film AA		Paper 600 with intensifying screens					
		No screens		F 1		F 2	
Density range	Latitude	Density range	Latitude	Density range	Latitude	Density range	Latitude
0.5-3.5	11	0.25-1.2	20	0.2-1.3	2.2	0.2-1.3	7.1

In 13) exposure latitude was determined from the same thickness-density curves, used for contrast assessment. Results are shown below:

Table 9

Exposure latitude (in mm) for A film and 600 and 610 paper for Fe[13)]

Film A		Paper with R7 screens			
Lead screens		600		610	
Density range	Latitude	Density range	Latitude	Density range	Latitude
1.2-2.8	3.0	0.4-1.0	2.0	0.4-1.0	3.3

No such data about gradient and latitude could be found for the Agfa-Gevaert Structurix IC paper.

2.5. Image quality

The radiographic image quality was investigated by use of the standard IQIs[9,11,15,16,18)], whereas in 12), 13) and 14) special penetrameters were used.

According to 16), the image quality investigation was made at 200 kV. Wire and step-and-hole IQIs were placed on a 25 mm steel plate and exposed to reach a density (above base and fog) of D_f = 2 for Industrex A film and 0.6 for the 610 paper. IQI sensitivities obtained thus were:

Table 10

Radiographic sensitivities for Industrex A film and 610 paper[16)]

Film/paper and screen	Wire IQI	Step-and-hole IQI
Industrex A, no screens	2%	3.2%
Industrex A, lead pack	1%	2%
Instant 610, high speed	2.5%	4%
Instant 610, standard	2.5%	4%
Instant 610, high definition	2%	3.6%

Nussmüller[9] investigated the radiographic quality of the 600 paper according to DIN 54109 using both X-rays (up to 300 kV) and Co-60 gamma rays. The results are presented on fig. 5 for steel.

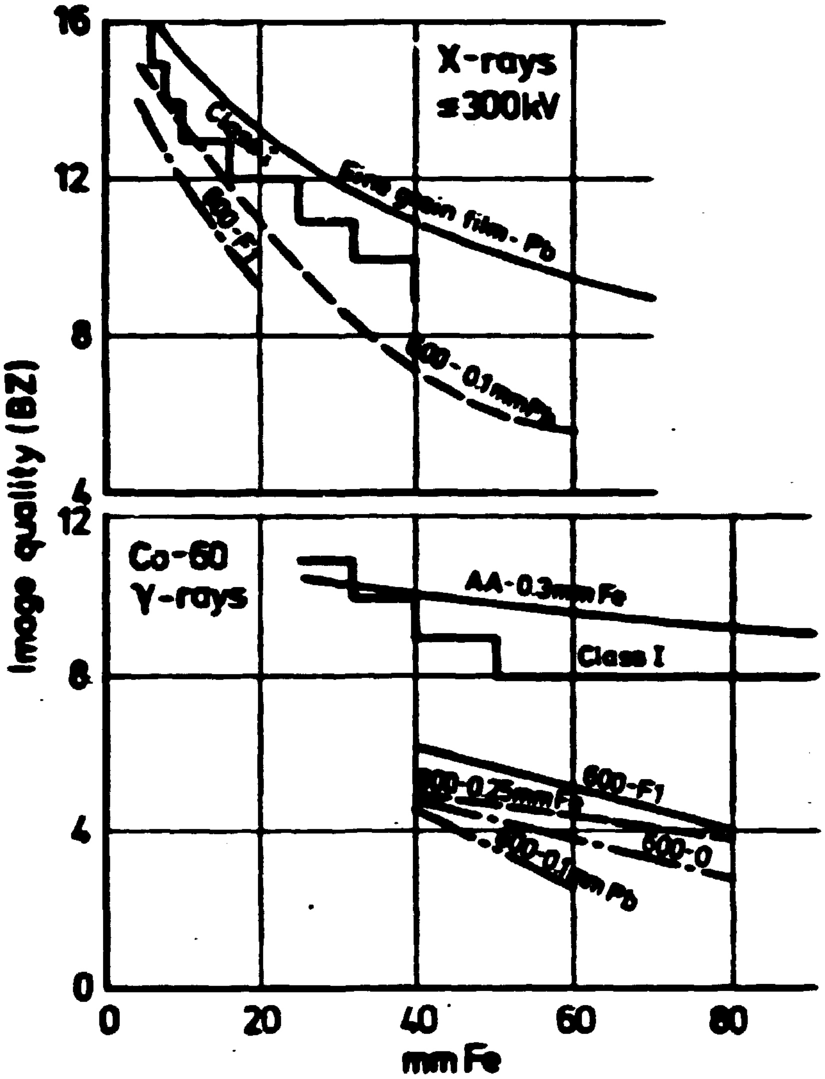

Fig. 5. Radiographic quality of Kodak Instant 600 paper[9].

The radiographic sensitivity of the 600 paper with F-1 and F-2 screens was investigated[15] for aluminium in the range from 3.2 to 89 mm using 45 to 160 kVcp. Comparison was made at density $D_p = 0.75$. For the F-1 screen, the IQI sensitivity reached using the MIL-Standard 453 penetrameter was from 1.3 to 3.5%. For the F-2 screen, it was below 2%, but slightly higher than that for the F-1 screen.

It is not possible to quote here some simple values for the IQI sensitivities reached by Ruault[13,14] for Al, because this author used some non-standard penetrameters.

Agfa-Gevaert[18] quotes only one value for the image quality of the Structurix IC paper with the IC type II screen measured at 150 kV on a 10 mm steel plate with wire type DIN IQI; 2% is quoted for paper at density D_p = 1.0 and 1.3% for the D7 film with lead screens at density D_f = 2.0.

2.6. Exposure charts

It was equally difficult to find complete information about exposure charts for the radiographic paper. Exposure charts for aluminium and steel taken on bromide paper were given in 1) (see fig. 6).

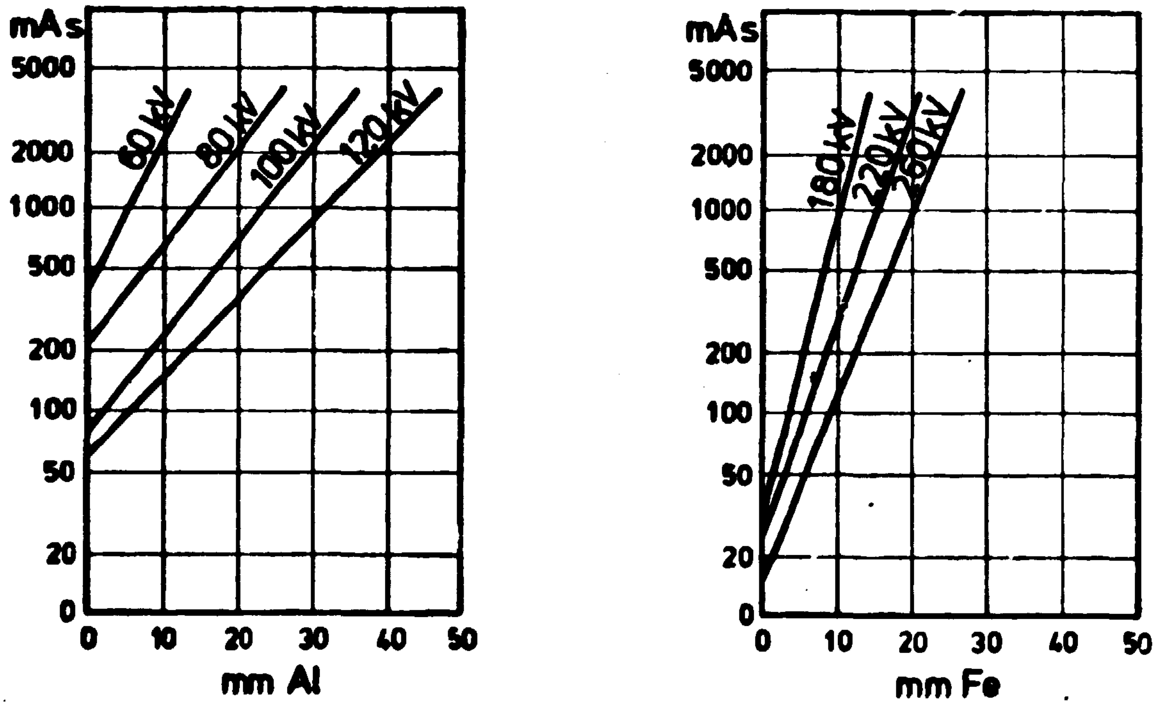

Fig. 6. Exposure charts for Al and Fe taken on bromide paper[1]
FFD = 1
Paper density D_p = 0.75

For the Industrex 600 paper, exposed with F-1 fluorescent intensifying screens, 15) gives an exposure chart for aluminium taken at 1.2 m at 25 to 150 kV cp (see fig. 7) for $D_p = 0.75$.

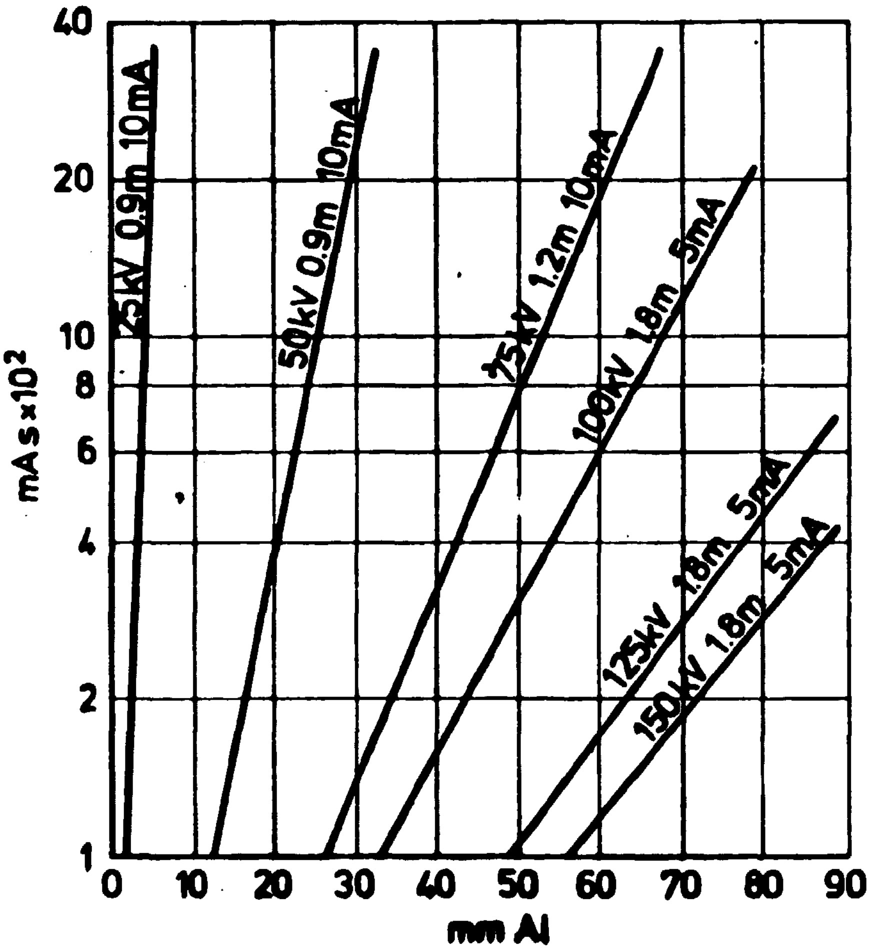

Fig. 7. Exposure chart for Al. Industrex 600 paper with F-1 screen. FFD = 1.2 m. $D_p = 0.75$[15].

Exposure charts for steel and the same 600 paper and F-1 screens are given in 9) for FFD = 0.8 m and $D_p = 0.75$ taken with 150, 200 and 300 kV X-rays as well as Co-60 gamma rays (see fig. 8).

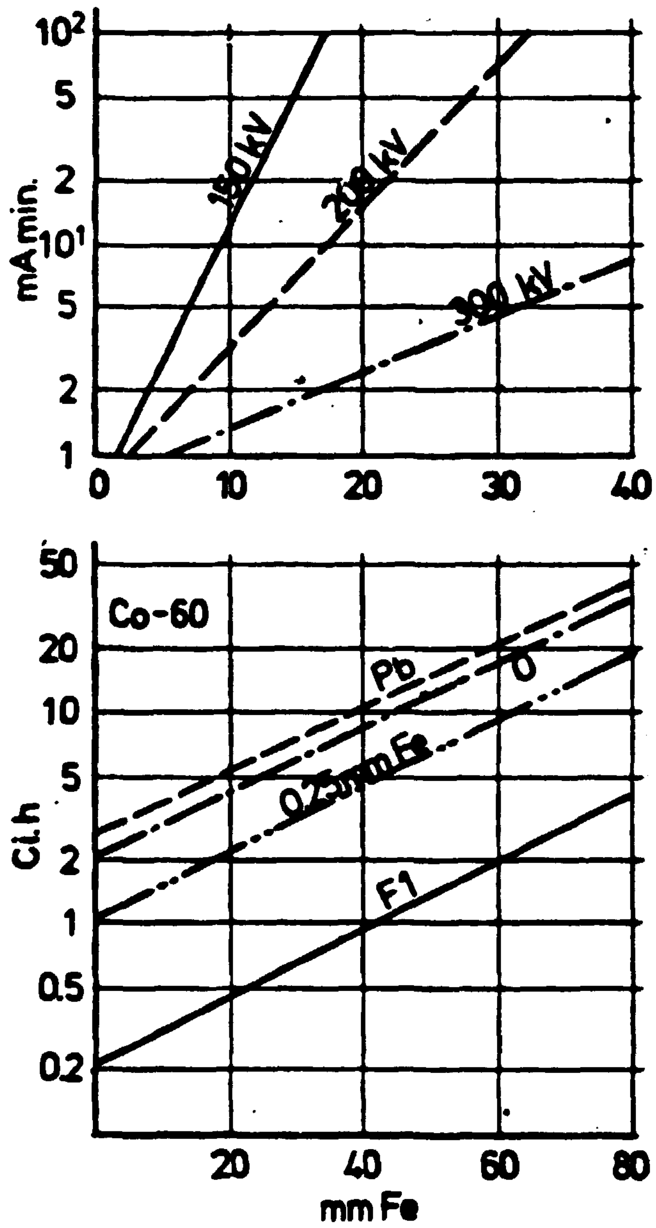

Fig. 8. Exposure charts for Fe. Industrex 600 paper with different intensifying screens. FFD = 0.8 m. D_p = 0.75[9].

Ruault[13] produced some exposure charts for Al on Industrex 600 paper using his new constant exposure technique (also described in 14). (See fig. 9). A comparison is also given on fig. 10 for the 600 and 610 paper. The FFD was 1 m and D_p = 0.7 on both figs. 9 and 10.

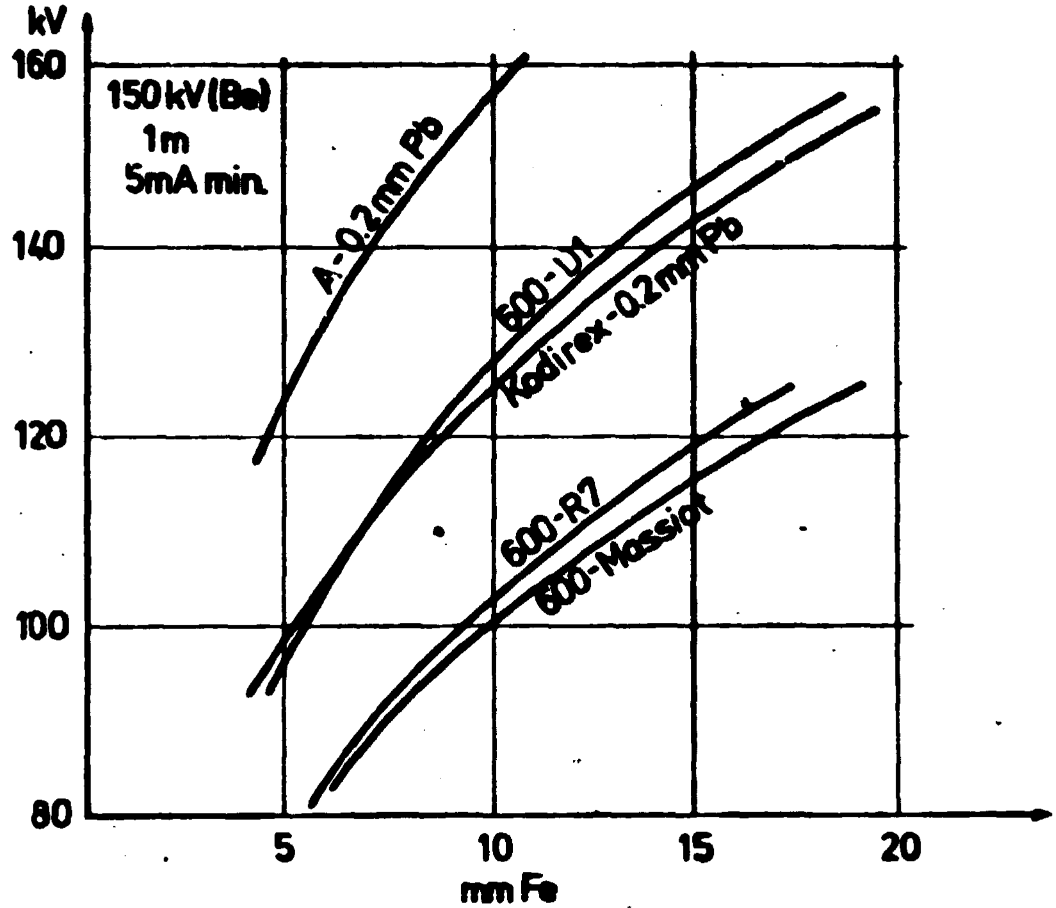

Fig. 9. Exposure charts for Al (at constant mA min exposure) for Industrex A film and 600 paper with different intensifying screens. FFD = 1 m. $D_f = 2.0$. $D_p = 0.7$[13].

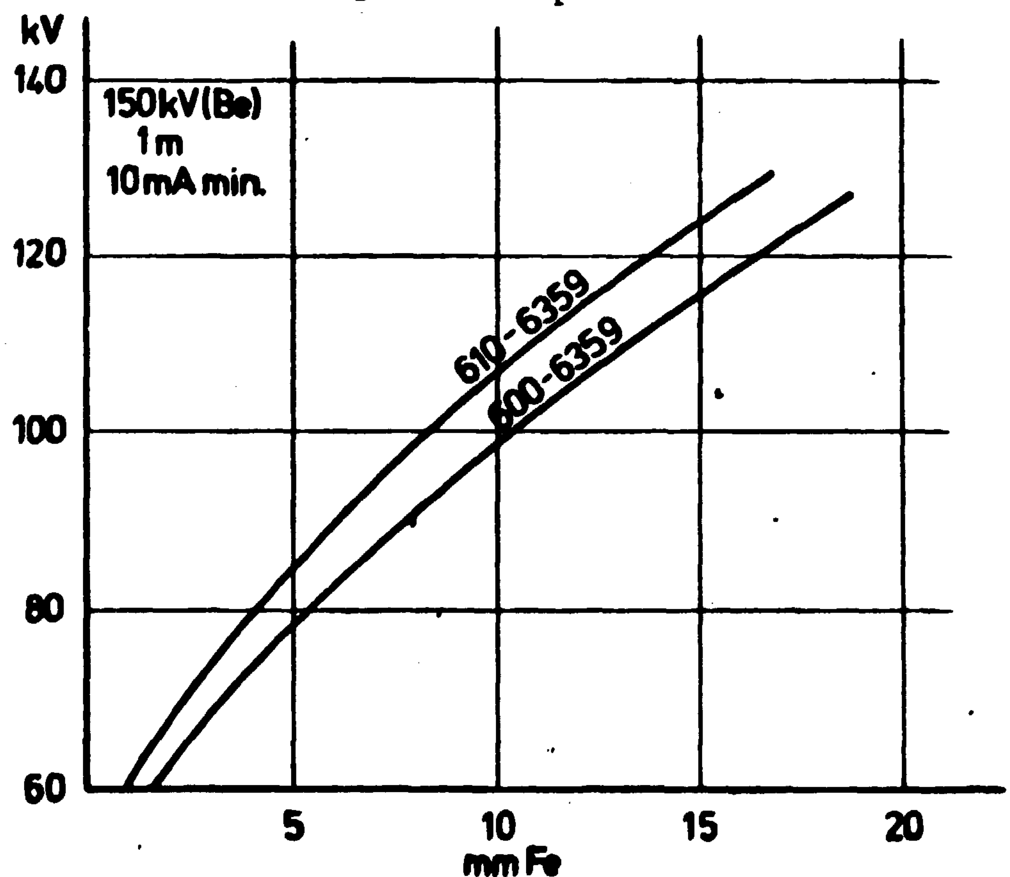

Fig. 10. Exposure charts for Fe. Industrex 600 and 610 paper with Massiot 6359 screens. FFD = 1 m. $D_p = 0.7$[13].

Agfa- Gevaert[18] gives comparative exposure charts for Al (see fig. 11) for the Structurix D7 film (no screens) and IC paper with IC type II screens.

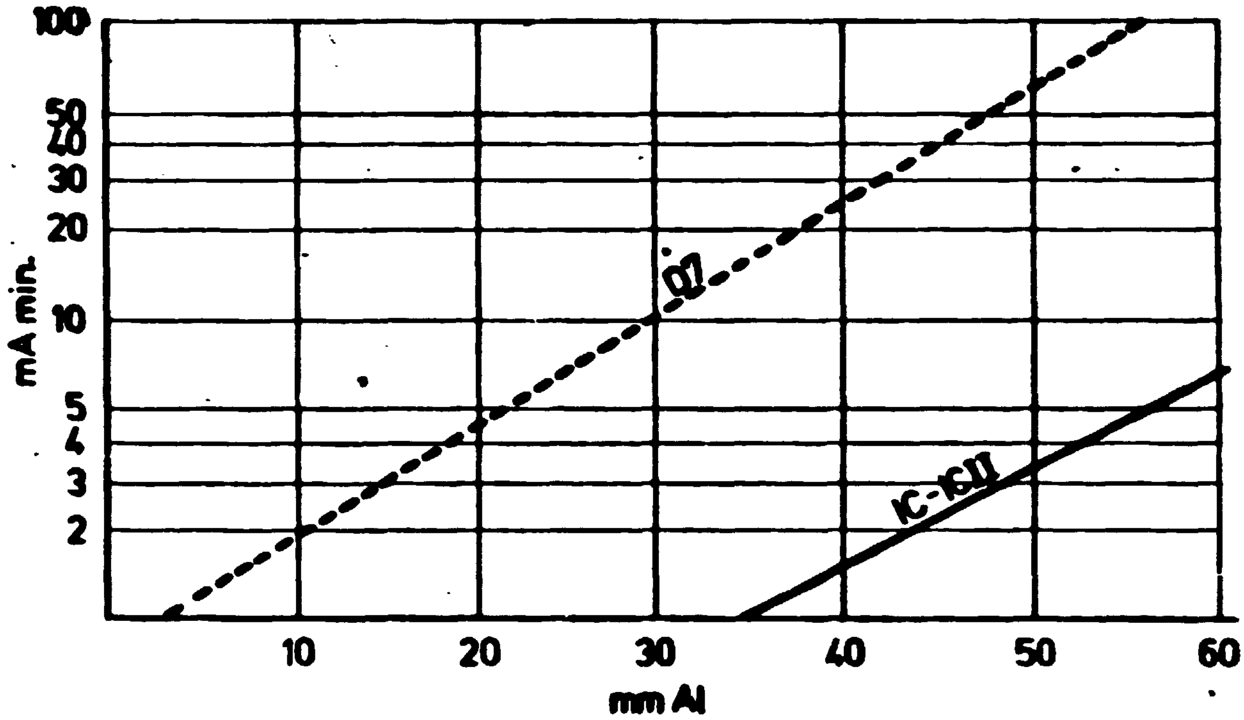

Fig. 11. Exposure chart for Al and X-rays. Structurix D7 (no screen) film and IC paper with IC type II screens[18].

On fig. 12 a similar chart is given for Fe.

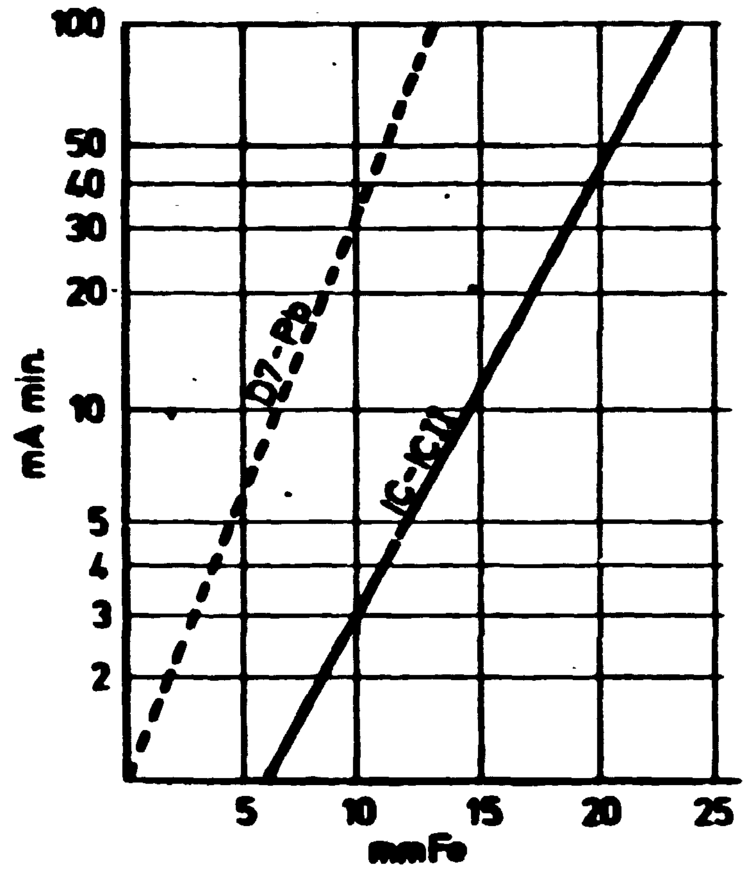

Fig. 12. Exposure chart for Fe and X-rays. Structurix D7 (lead screens) film and IC paper with IC type II screens[18].

3. SCOPE OF THE INVESTIGATION

As mentioned before, the main purpose of this investigation was to compare the radiographic quality of paper with that of film. This was done by using some specially designed as well as conventional Image Quality Indicators (IQI). Besides cheking the quality of the radiographic image obtained on paper, several other properties were also investigated. The scope of the investigation is described below.

The investigation started with the production of characteristic curves for the Agfa-Gevaert IC, and Kodak 600 and 610 radiographic papers. Both brands were first exposed without an intensifying screen. Then the IC paper was exposed with IC II screens, while the 600 and 610 papers were exposed with XO, F1 and F2 screens.

The characteristic curves were taken at 30 to 50 kV using a beryllium-window X-ray tube. For the sake of comparison, characteristic curves of Agfa-Gevaert D4 and Kodak C and D X-ray films were also taken.

For the radiography of U/Al MTR fuel plates[12], 45 kV proved best for the quality control of these plates. Therefore characteristic curves were produced at this voltage for the IC, 600 and 610 papers as well as for the D4 and C films.

Characteristic curves were also produced using a 180 and 300 kV X-ray machine. With the 180 kV machine, characteristic curves were made at 100 kV; 190 kV was used with the 300 kV machine. For both machines, IC, 600 and 610 papers as well as C film (exposed with 0.05 + 0.10 mm lead screens) were used.

For the radiography of U/Al blocks[12], 150 kV proved to give the best results. Therefore characteristic curves were also produced at this voltage using the 300 kV X-ray machine.

Paper radiography is also used at Risø for the control of fiber-reinforced composite materials. Samples of these materials were radiographed at 10 kV, and therefore characteristic curves for the IC and 600 papers were also produced at this voltage.

Other sensitometric properties of the radiographic paper (such as relative speed and contrast) could be calculated from the characteristic curves. These properties were used to compare the various paper and screen combinations as well as for comparison with X-ray films.

To check the quality of the radiographic image, it is common practive to use Image Quality Indicators. Among the many typesof IQIs, the wire type and the step-and-hole type are internationally recommended by the ISO[19].

The wire-type IQI was used to control the radiographic quality of X-ray pictures of aluminium and steel. It was, however, impossible to use either of the ISO IQIs to control the quality of radiographs of U/Al plates or blocks[12], as no IQIs made of U/Al alloys are available. Therefore the quality of the radiographs of the MTR fuel plates was assessed by using an aluminium step wedge (contrast sensitivity); to assess the radiographic quality of the U/Al blocks, a calibration block was used in which holes of different diameters were drilled.

The radiographic quality of fiber-reinforced composite materials[20] was evaluated in the same way as that of the U/Al alloy.

For the different paper and intensifying screen combinations, exposure charts for aluminium (up to 70 mm) and steel (up to 35 mm) were produced. Here a 50 kV X-ray machine with beryllium window tube as well as a 180 kV X-ray machine were used for aluminium (25 to 130 kV range), while a 300 kV X-ray machine was used (100 to 300 kV range) for steel. The exposure curves were compared with similar curves for X-ray films.

Besides the basic investigations described above, some additional tests were performed. They comprised the following: the sharpness of the radiographic image on paper (or film) exposed with intensifying screens depends largely on good contact between the paper (or film) and the screen. This factor was investigated for rigid, metal cassettes of different sizes (up to 50 x 60 cm) and manufacture. As some of the cassettes did not ensure good contact, special procedures were adopted. In the very low kilovoltage range necessary for radiography of composite materials, plastic vacuum cassettes were used.

Throughout the investigation both Agfa-Gevaert and Kodak papers were used. They were developed in the standard processing units and chemicals of these firms. To check the influence of the processing chemicals on the sensitometric properties of the radiographic paper, Kodak paper was processed in Agfa-Gevaert chemicals and Agfa-Gevaert paper was developed in Kodak chemicals, and the results were compared.

Paper radiographs were made on different sizes of paper, originating from different batches. Also different sizes of intensifying screens and cassettes were used. Therefore it was checked if similar results are obtained when different batches of paper and screens are used.

4. EQUIPMENT

During the present investigation three types of X-ray machine, three brands of radiographic paper (processed in two different processors), two types of densitometer and three types of IQI were used. They are all described below.

4.1. X-ray machines

For the quality control of MTR fuel plates[12], a 50 kV X-ray machine was used. The same machine was used throughout this investigation for U/Al and Al specimens. The X-ray machine was a Baltographe BF 50/20, which could be used from 5 to 50 kV. It is a constant potential machine and has a beryllium window tube with a 0.5 mm focus. At 50 kV, a 10 mA load is possible and at 25 kV a 20 mA load.

On fig. 13 the Baltographe BF 50/20 is shown while taking radiographs of MTR plates on 50 x 60 cm radiographic paper.

For thicker Al specimens, an Andrex 180 kV X-ray machine was used. It is a single tank unit with a 2.3 mm focus X-ray tube with a 5 mA maximum load.

The quality control of U/Al blocks for the production of MTR fuel elements[12] was performed with an Andrex 300 kV X-ray machine. The same machine was used for steel specimens. It is a single tank unit with a 3.0 mm focus X-ray tube with a 5 mA maximum load.

Figure 14 shows the 300 kV Andrex machine while taking radiographs of U/Al blocks. The Andrex 180 kV machine was used on the same tube stand. It is of the same type, but smaller and lighter.

4.2. Radiographic paper, intensifying screens and processors

During the present investigation Kodak Industrex Instant 600 (manufactured in the USA) and 610 (manufactured in France) radiographic paper was used as well as the Agfa-Gevaert Structurix IC paper. A stabilization processing is used for these papers, which is described by Kodak in the following way

"Briefly, stabilization processing is a method of producing radiographs on paper much faster than is possible by conventional develop-stop-fix-wash processing. For example, exposed Kodak Industrex Instant 600 paper processed by stabilization makes quality, ready-to-use radiographs available in seconds. These stabilized radiographs are not permanent because the chemical reactions within the emulsion have been stopped only temporarily. They will, however, last long enough to serve a number of practical purposes. In fact, stabilized radiographs

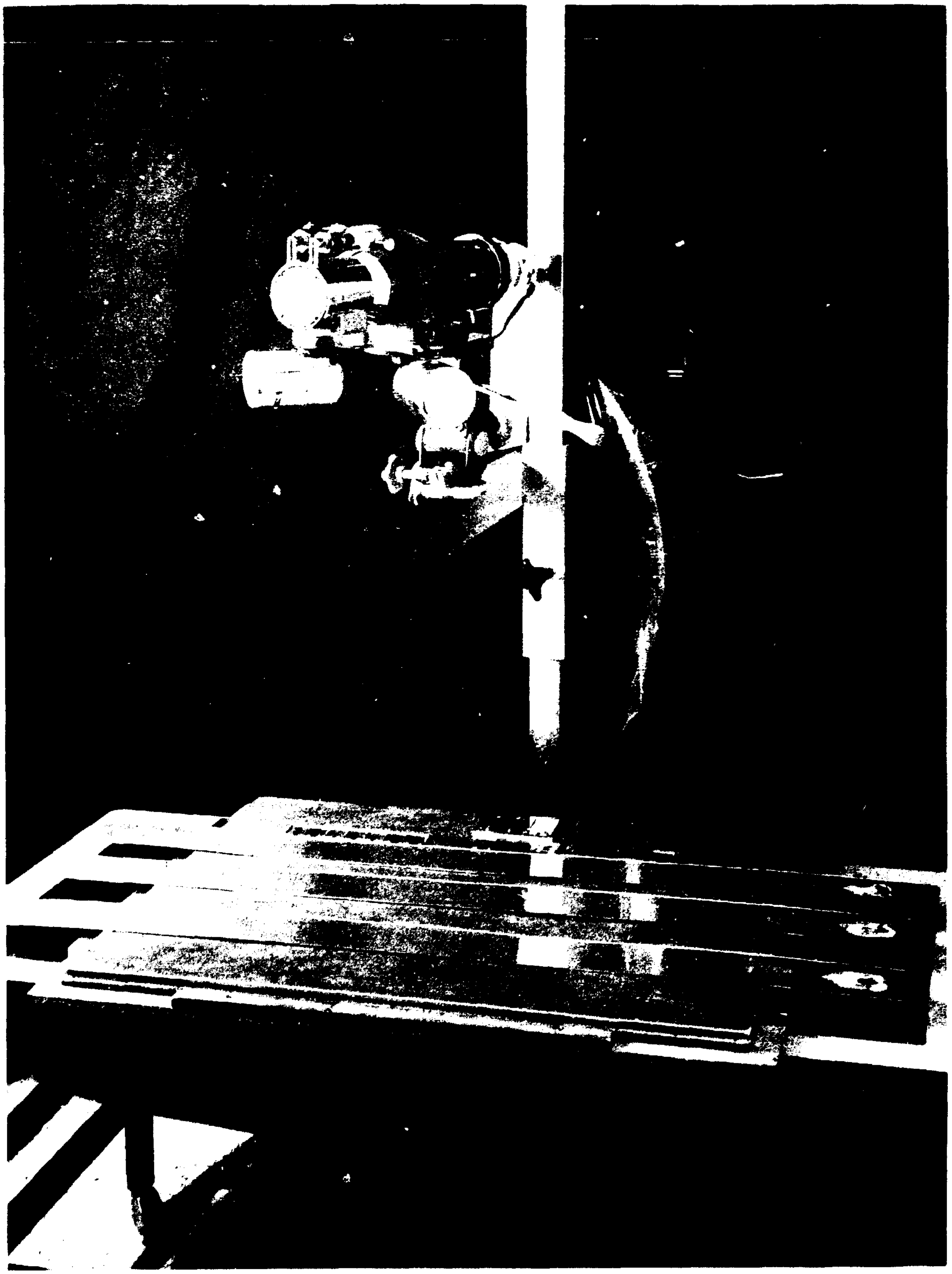

Fig. 13. Taking radiographs of the MTR fuel plates with the Baltographe 50/20 on 50 x 60 cm radiographic paper.

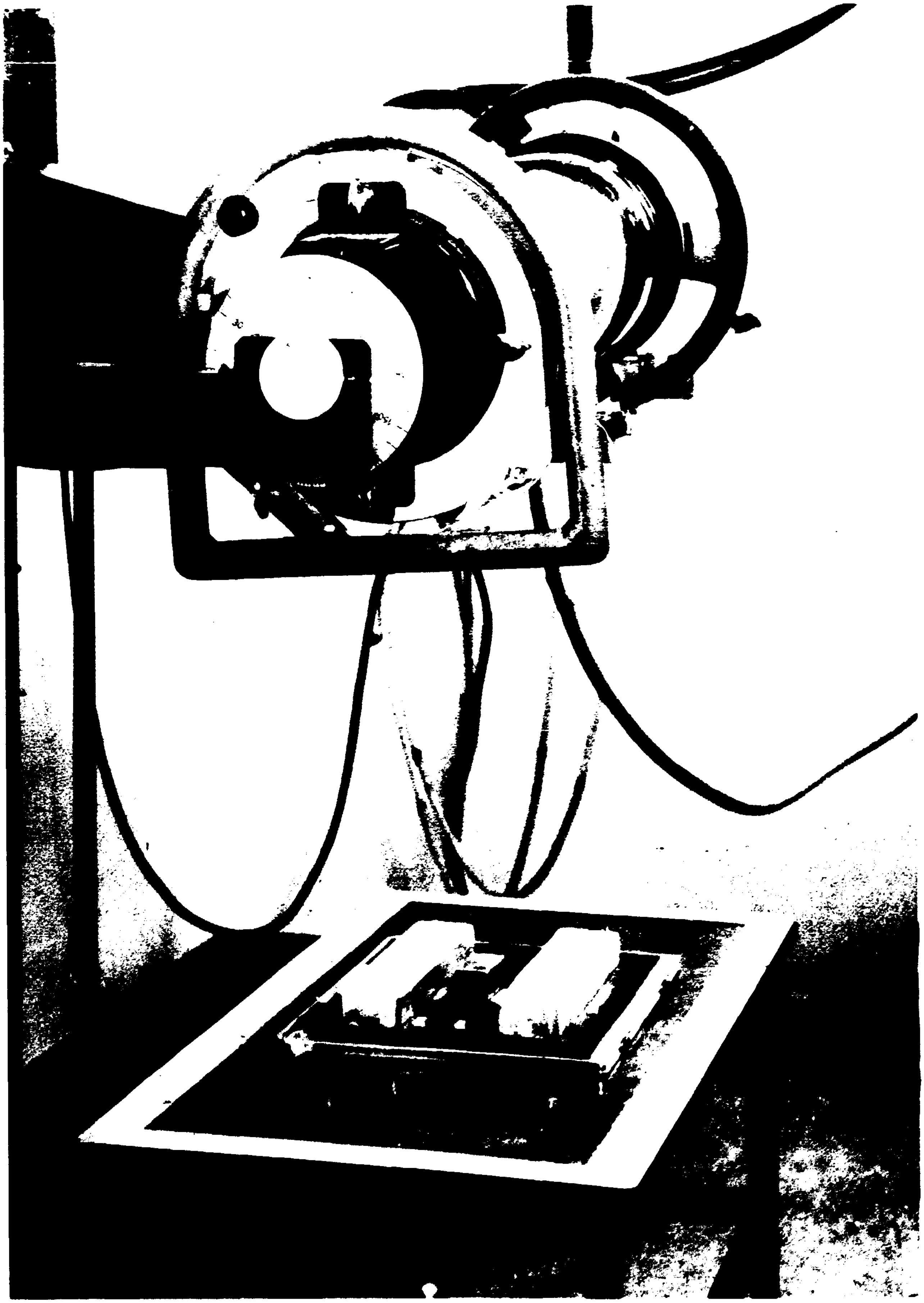

Fig. 14. Taking radiographs of the U/Al blocks for the MTR fuel elements with the Andrex 300 kV X-ray machine.

often remain unchanged for many months if they are not exposed to strong light, high temperature, or excessive humidity.

Stabilization processing is a machine operation in which radiographs on paper are processed in about 10 seconds and leave the processor in a slightly damp condition. They dry completely in a few minutes.

The main differences between stabilization processing and ordinary radiographic processing are in the speed of activation (development) and in the method of treating the unexposed light-sensitive silver halide left in the emulsion after development. In conventional processing, the unused silver halide is dissolved by the fixer and any traces of soluble silver salts left after fixing are removed by subsequent washing. The resulting radiographs are stable for long periods. In stabilization processing, however, the silver halide is converted to compounds which are only temporarily stable and the radiographs have a limited keeping time. However, stablized radiographs can be made permanent by fixing and washing after they have served their initial purpose.

In papers designed for stabilization processing, developing agents are incorporated in the paper emulsion. Development is achieved by applying an alkaline activator to the emulsion surface. The stabilizer is then applied to neutralise the activator and to convert any remaining silver halide to relatively stable, colorless compounds. Ordinary photographic papers or X-ray films cannot be developed by this process because there is no developing agent present in either the emulsion or the activator. However, a stabilization paper with developing agents in the emulsion can be hand-processed in X-ray processing chemicals.

In stabilization processing, you exchange a measure of radiograph stability for the following advantages:

1. Speed. Stabilization processing is fast. Radiographs are ready for use in seconds.
2. Simplicity. The process is adaptable to uncomplicated mechanical systems.
3. Space saving. Darkroom space and plumbing needs are greatly reduced. In fact, some applications of the process do not require a darkroom.

4. Water saving. Stabilized radiographs do not require washing.
5. Greater uniformity. Mechanically processed radiographs have better day-to-day uniformity in density than those processed manually.

Important points for successful stabilization processing.

1. Correct exposure is essential because development time is constant.
2. Keep the processor clean. Follow the mahufacturer's recommendations for cleaning and maintenance.
3. Don't overwork the chemical solutions. Observe the manufacturer's recommendations in regard to the capacity and renewal of solutions.
4. Make sure the processing trays in the machine are dry before loading them with chemicals because some stabilization solutions are not compatible with water.
5. Avoid contamination of the activator with the stabilizer. This results in chemical fog on the radiographs.
6. Avoid handling unprocessed paper after handling stabilized radiographs. The radiographs are impregnated with chemicals that easily mark or stain unprocessed material.
7. Do not wash stabilized radiographs unless they have been fixed in an ordinary fixing bath. Washing without fixing makes the radiograph sensitive to light.
8. Stabilized radiographs must not be heat-dried. The combination of heat and moisture stains them an overall yellowish-brown.
9. Because stabilized radiographs are impregnated with chemicals, do not file them in contact with processed X-ray films or other valuable material.

For handling and storage of the radiographic paper the following rules are recommended:

The paper can be handled under the light transmitted by a Kodak Safelight Filter, No. 6B (brown) or OC (light amber) in a suitable safelight lamp with a 15-watt bulb at a distance of 1.2 m from the working surface. With the OC Filter, a brightness level approximately four times that of the No. 6B Filter is obtained.

Before exposure and processing, store the paper under uniform conditions; 21 - 24^{o}C, and 40 to 50 percent relative humidity are recommended. After exposure and before processing, the paper may be stored for four days without any significant effect on speed and contrast. After exposure and after stabilization processing, examine the radiograph and dry thoroughly before storing. If the processed radiograph is to be kept longer than 6 to 10 weaks, fix and wash as recommended. Store the radiograph in a dry, dust-free place, away from harmful gasses and chemicals. After exposure and post-stabilization processing, radiographs have commercial keeping .tability.

Radiographs are damp on leaving the processor, but at room temperatures will dry completely, without curl, within a few minutes. Drying radiographs on hot drum machines is not recommended unless they have been fixed and washed. (It has, however, proved possible to dry radiographs on a hot drum machine if the drum temperature does not exceed 50°C).

The keeping time of stabilized radiographs is limited because the chemical reactions within the emulsion have been stopped only temporarily. Deterioration will eventually follow exposure to heat, light, and humidity. The time taken to produce a change in the condition of a radiograph depends upon the degree and combination of these factors. Radiographs made on radiographic paper will keep for many months if the storage conditions are favorable (21 to 24°C and 40 to 50 percent relative humidity), and if the chemicals were in good conditic.. at the time of processing.

When permanent radiographs are required, the following post-stabilization processing is recommended:

Fix the stabilized radiographs for 3 minutes in Kodak Liquid X-ray Fixer or for 5 minutes in Kodak X-ray Fixer at 18 to 21°C. Wash at least 30 minutes in running water at 18 to 21°C. Dry in a dust-free area on any matte dryer if available. Otherwise, dry, mounted back to back on standard X-ray developing hangers, in a low-heat dryer".

With the Kodak 600 and 610 paper, the Kodak F-1 and F-2 fluorescent intensifying screens were used. As equivalent to the F-1 type, X-omatic Regular Screens (XO) were also used. With the Agfa-Gevaert IC, paper Structurix IC fluorescent screens type II (IC II) were used.

The Kodak 600 and 610 paper was processed in the Kodak Industrex Instant Processor Model P-1. The general view of the

P-1 processor is shown on fig. 15, whereas fig. 16 shows the inside of the processor (lid removed). Figure 17 shows a schematic diagram of the P-1 machine.

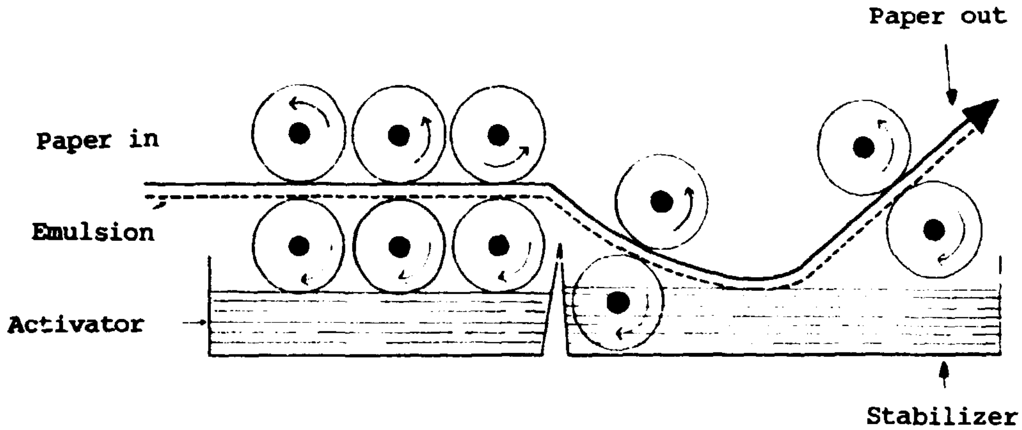

Fig. 17. Schematic diagram of the P-1 processor.

The Agfa-Gevaert Structurix IC paper can be processed in similar processing units: the IC 35 (maximum paper width 35 cm) or the IC 50 (maximum 54 cm). At Risø the IC 50 is used (paper up to 50 x 60 cm is used). Figure 18 shows the schematic diagram of the IC processor.

To speed up the process of drying the large 50 x 60 cm paper radiographs, an Agfa-Gevaert Rapidoprint DR 70 dryer was added to the Structurix IC 50 processor (see fig. 19). Thus the radiographic paper was processed and dried in one single operation. Although the DR 70 unit is a 4 kW dryer, it cannot dry the 50 x 60 cm paper completely. Nevertheless, this combination of processor-dryer proved satisfactory for the number of radiographs taken during the production of the MTR fuel elements.

For the processing of the Kodak 600 and 610 paper, Kodak Industrex Instant chemicals were used.

Two solutions are required for processing Kodak Industrex Instant Paper: Kodak Industrex Instant Activator and Kodak Industrex Instant Stabilizer. These solutions are supplied, ready to use, in plastic bottles of the correct size and shape to fit into the two wells in the processor. In stabilization processing the temperature of solutions is not critical: 20°C is ideal but the useful range is 18 to 24°C.

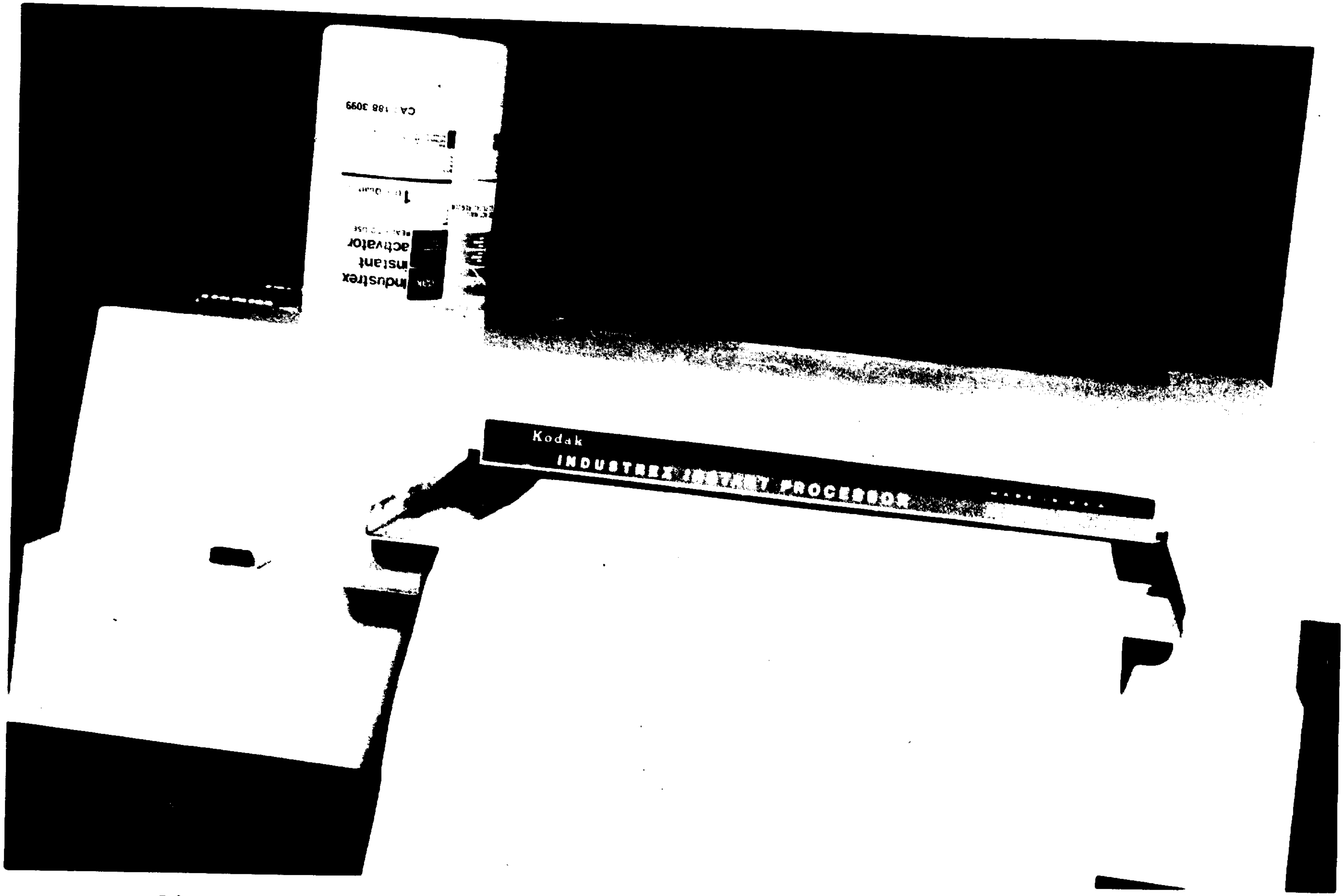

Fig. 15. General view of the Kodak Industrex Instant Processor Model P-1.

Fig. 16. Inside view of the P-1 processor.

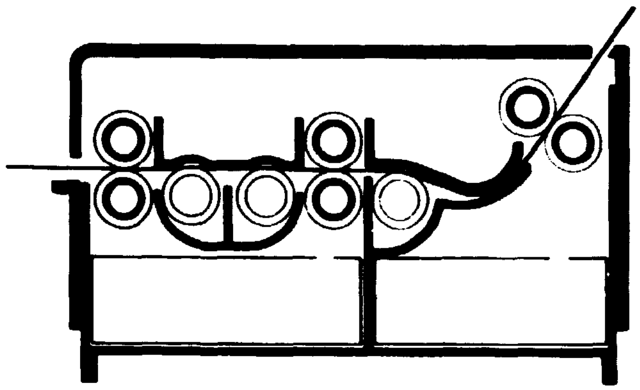

Fig. 18. Schematic diagram of the IC processor.

Discard the solutions and clean the processor weakly, or when about 13 m^2 of paper have been processed.

Kodak Industrex Instant Chemicals will keep indefinitely in the original sealed packages, but storage temperatures should not exceed 38°C.

In the Agfa-Gevaert processor, the IC paper was processed in the Agfa-Gevaert solutions, which are described as follows:

"The activator G 126 is strongly alkaline, so that development is virtually instantaneous. Since the development reaction proper only occurs at the moment that the alkali of the activator enters into contact with the developing agent in the emulsion, aerial oxidation of the activator is avoided. The activator has therefore a very long life.

The active component of G 326 stabilizer is ammonium thiocyanate NH, CNS, which converts unexposed silver chloride into a colourless and insoluble silver thiocyanate complex of such little sensitivity to light that it can be allowed to remain in the emulsion without objection".

4.3. Paper and film densitometers

Optical densities of the radiographic paper were measured with the Super Speedmaster reflection densitometer Model R 70 B (Electronics Systems Engineering). With this densitometer (see fig. 20), reflection densities up to 2.5 with an accuracy of ± 0.02 can be measured. The aperture size in this densitometer is 1.6 mm.

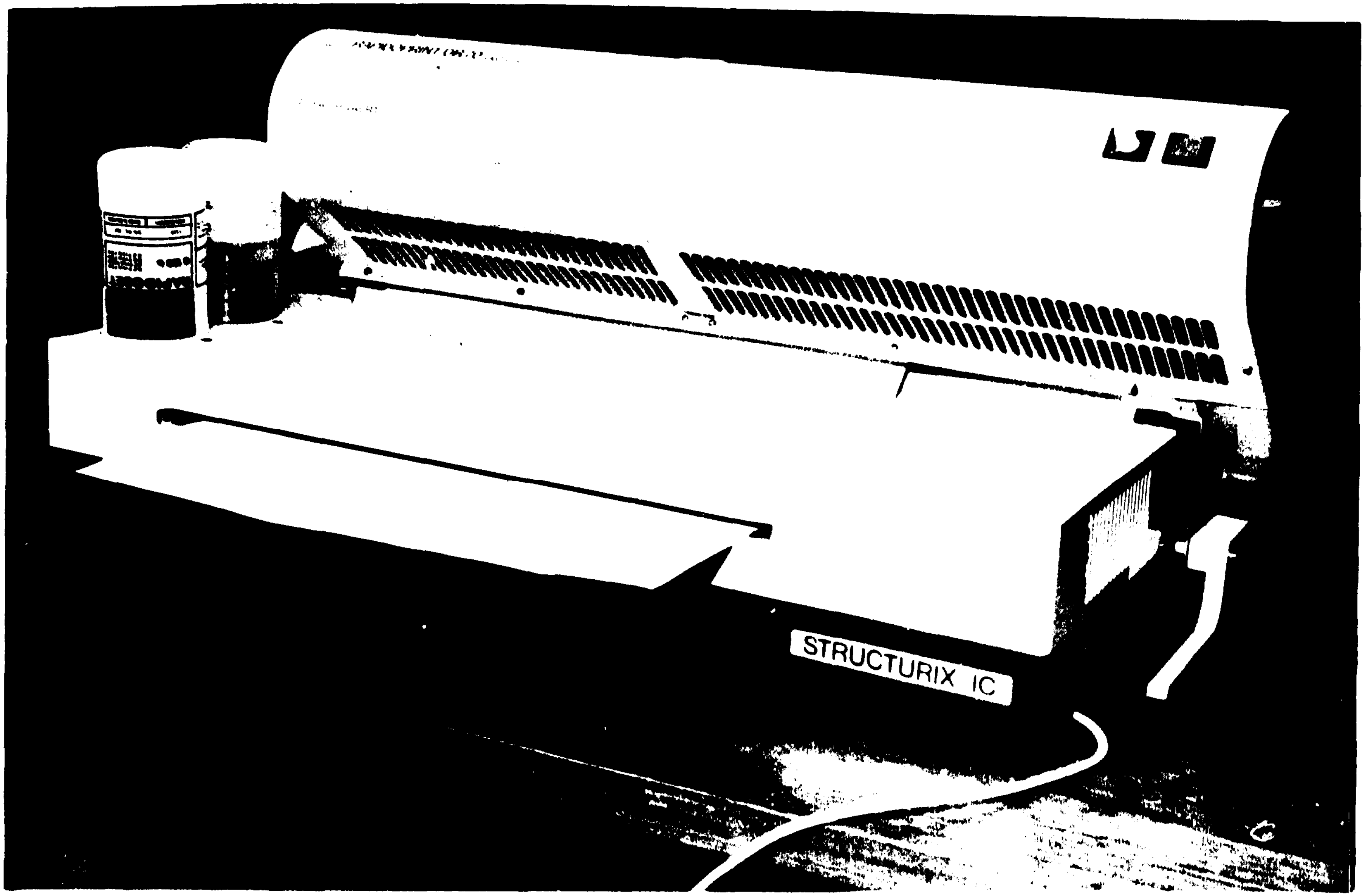

Fig. 19. Agfa-Gevaert IC 50 processor with Rapidoprint DR70 dryer.

Fig. 20. Reflection densitometer Model R 70 B.

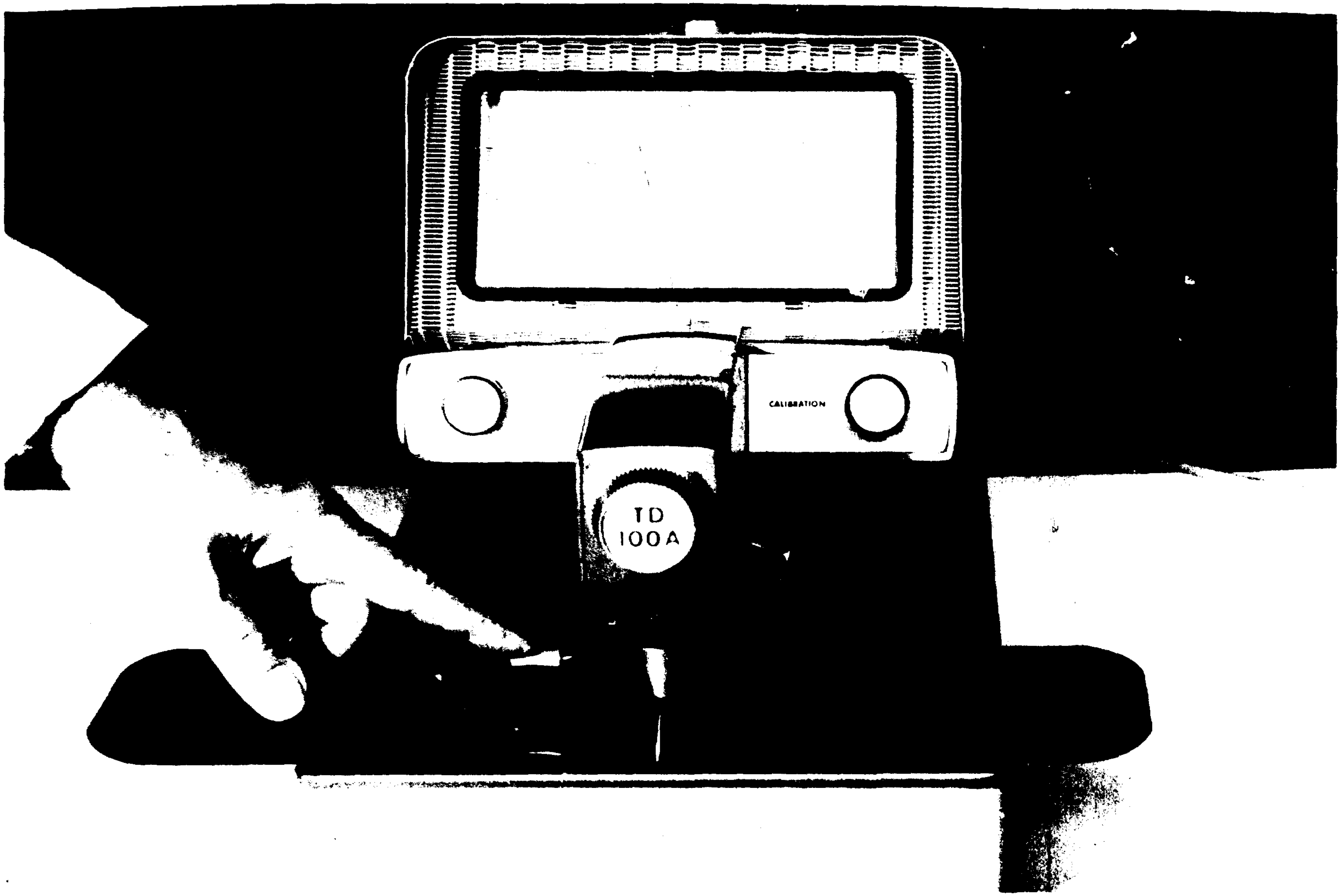

Fig. 21. Transmission densitometer Macbeth Quanta Log Model TD 100 A.

X-ray film densities were measured with the Macbeth Quanta Log Model TD 100 A transmission densitometer (see fig. 21). With this densitometer densities up to 4.0 can be measured with an accuracy of ± 0.02 (it is possible to measure densities up to 5.0 with a decreased accuracy). Apertures of 1, 1.6, 2 and 3 mm may be used.

4.4. Image quality indicators

To check the quality of aluminium and steel specimen radiographs, wiretype ISO[19] IQIs were used (see bottom on fig. 22). The quality of U/Al blocks was assessed by using special IQIs produced from a 30 mm thick U/Al block. Near the top of the block, five circular holes were drilled with diameters of 1.5, 0.9, 0.6, 0.5 and 0.4 mm, which correspond to 5, 3, 2, 1.67 and 1.33% of the block thickness (see top of fig. 22). The U/Al blocks were radiographed together with the above IQI, as can be seen on fig. 14 (the IQI block is located in between the two U/Al blocks). On the top of the IQI block a 0.6 mm U/Al plate was placed in which holes with diameters corresponding to 1, 2 and 4 times the plate thickness (0.6, 1.2 and 2.4 mm) were drilled. This plate corresponds with the ASTM type of penetrameter.

For the quality control of U/Al plates (a 0.54 mm U/Al core sandwiched between two 0.46 mm Al plates), it was not possible to use the conventional type of IQI. Therefore the quality of the radiographic image was judged from density readings under an Al step wedge (see middle of fig. 22) (steps from 4.0 to 6.5 mm in 0.1 mm increments)[12]. During the routine examination of the fuel plates a simplified step wedge was used consisting of three steps: 5.0, 5.5 and 6.0 mm of Al (seen in the upper part of fig. 13).

The method of assessing the quality of U/Al plates by using an Al step wedge is based on a previous investigation[21] that was applied to paper radiographs[12].

4.5. Al and Fe step wedges

The exposure charts for aluminium and steel were produced with the help of step wedges. The step wedges were produced from 65 mm wide plates. Each step has the width of 35 mm. Up

Fig. 22. ISO IQI's (Al and Fe), Al step wedge, U/Al IQI.

to 10 mm, a step wedge of ten 1 mm plates was used. For greater thicknesses, step wedges of 2.5 mm thick plates were used, (2.5 to 25 mm). Exposure charts for even greater thicknesses were produced by adding 10 or 30 mm plates under the 2.5 mm step wedge (see fig. 23).

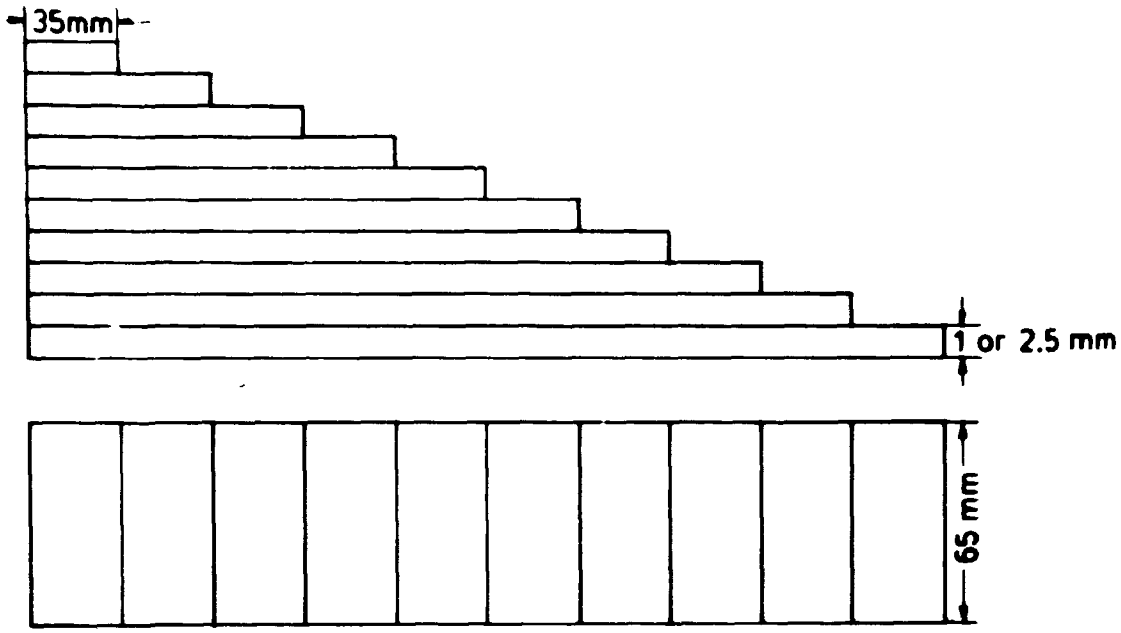

Fig. 23. Al and Fe step wedges.

5. CHARACTERISTIC CURVES

Characteristic curves were taken using all the three X-ray machines (50, 180 and 300 kV) as well as all the combinations of radiographic paper and screens. To be able to compare the sensitometric properties of the paper with those of the X-ray film, some brands of the X-ray film were also exposed under similar conditions and characteristic curves were produced.

The sensitometric properties of the radiographic material depend on the quality of the radiation reaching it. Taking this into account the characteristic curves were produced using radiation of a quality similar to that used in routine radiography.

Table 11. Characteristic curves (numbers refer to figures on which the curves are shown).

X-ray machine			B 50							A 180	A 300	
kV			30	35	40	45	50	45	10	100	190	150
Paper/ film	Screen	Filter										
IC	0	Pl. 519		24,26,28	24,26,28	24,26,28	24,26,28					
IC	IC II	Pl. 519	24,26,28	24,26,28	24,26,28	24,26,28	24,26,28	32				
600	0	Pl. 519		25,26,29	25,26,29	25,26,29	25,26,29					
600	F2	Pl. 519	25,26,29	25,26,29	25,26,29	25,26,29	25,26,29					
600	F1	Pl. 519	25,26,29	25,26,29	25,26,29	25,26,29	25,26,29					
600	X0	Pl. 519	25,26,29	25,26,29	25,26,29	25,26,29	25,26,29	32				
610	0	Pl. 519				25,26,30	25,26,30					
610	F2	Pl. 519	25,26,30	25,26,39	25,26,39	25,26,30	25,26,30					
610	F1	Pl. 519	25.26.30	25.26.30	25.26.30	25.26.30	25.26.30					
610	X0	Pl. 519	25.26.30	25.26.30	25.26.30	25.26.30	25.26.30	32				
D4	0	Pl. 519	27,31	27,31	27,31	27,31	27,31					
C	0	Pl. 519	27,31	27,31	27,31	27,31	27,31	32				
D	0	Pl. 519	27,31	27,31	27,31	27,31	27,31	32				
IC	0	0							33			
600	0	0							33			
IC	0	30 mm Al								34		
IC	IC II	30 mm Al								34		
600	0	30 mm Al								34		
600	F2	30 mm Al								34		
600	F1	30 mm Al								34		
600	X0	30 mm Al								34		
610	0	30 mm Al								34		
610	F2	30 mm Al								34		
610	F1	30 mm Al								34		
610	X0	30 mm Al								34		
C	0.05 + 0.10 Pb	30 mm Al								34		
IC	IC II	20 mm Cu									34	
600	F1	20 mm Cu									34	
610	F1	20 mm Cu									34	
C	0.05 + 0.10 Pb	20 mm Cu									34	
IC	IC II	0										35
600	X0	0										35
610	X0	0										35
C	0.05 + 0.10 Pb	0										35

In the low voltage range, soft X-rays are used for the quality control of MTR fuel plates. Therefore one of such plates (No. 519) was used as filter during the production of characteristic curves. The filter plate was placed at the X-ray tube window to equalize the effect of uneven uranium distribution in the plate on paper (or film) density.

Characteristic curves at 10 kV (voltage range used for radiography of fiber composites) were taken without filter.

In the intermdiate voltage range, a 30 mm aluminium filter was used at 100 kV and a 20 mm copper filter at 190 kV. 20 mm of Cu was found to be equivalent to 30 mm of U/Al alloy used for the production of cast blocks, from which the MTR fuel plates are then produced.

Table 11 gives an outline of the characteristic curves produced during this investigation.

5.1. Low voltage range

As mentioned before, a soft X-ray machine was used for the radiographic control of the MTR fuel plates[12). With this machine (Baltographe BF 50/20) characteristic curves of Agfa Gevaert Structurix IC and Kodak Industrex Instant 600 and 610 paper were taken at voltages ranging from 30 to 50 kV.

To have the same radiation quality reaching the paper (or film) under exposure as during actual radiogrphy of the fuel plate, a filter consisting of one of the fuel plates was placed between the X-ray tube and the paper (or film). This fuel plate (No. 519) was placed at the X-ray tube window. Thus it produced no image on the paper.

The radiographic paper was exposed in rigid aluminium cassettes, whereas X-ray film (exposed for comparison with the paper) was exposed in paper cassettes (as no intensifying screens were used).

All the curves were taken at 1m FFD and paper or film densities were measured using the densitometers described in 4.3. above. These densities were thereafter plotted as a function of logarithm of exposure (in mAmin). The results of these measurements are shown on the following illustrations.

The first set of curves gives a comparison between characteristic curves taken without intensifying screens (marked "O") and those taken with the screens, for voltages from 30 to 50 kV.

Figure 24 gives such a set of curves for the IC paper exposed without and with IC II screens. For 30 kV it was not possible to produce characteristic curves for the IC paper exposed without intensifying screens, as the required exposure times are impractically long.

Figure 25 gives a similar set of curves for the Kodak 600 and 610 paper exposed without and with X0, F1 and F2 intensifying screens. Also here it was impossible to produce the curves without screens for 30 kV for both the 600 and 610 brands, as well as for the less sensitive 610 at 35 and 40 kV.

Finally, figure 26 gives a direct comparison of the IC and 600 and 610 paper in the same kilovoltage range.

To be able to compare the sensitometric properties of the radiographic paper with those of the X-ray film, characteristic curves of the Agfa-Gevaert Structurix D4 and Kodak Industrex C and D film were taken under the same exposure conditions as for the radiographic paper. The X-ray films were exposed without intensifying screens. The results are shown on fig. 27.

The next set of curves gives a different presentation of the same results. Here, for one type of paper and intensifying screen, all the characteristic curves taken at 30 to 50 kV are presented together.

Figure 28 gives such a set of curves for the IC paper; fig. 29 shows similar results for the 600 paper, whereas fig. 30 shows the curves for the 610 paper.

Figure 31 shows similar sets of curves for X-ray films: Agfa-Gevaert D4 and Kodak C and D (exposed without screens).

For the radiographic control of the MTR fuel plates on radiographic paper, 45 kV was found to be best, as both the uranium distribution and the location of the U/Al core can be assessed on the same radiograph.

Figure 32 gives all the characteristic curves taken at this voltage.

As mentioned before, paper radiography is also used at Risø for the control of fiber-reinforced composite materials[13]. Samples of these materials were examined in the 10 kV range, therefore characteristic curves for the IC and 600 paper were taken at this voltage (see fig. 33). A plastic cassette was used with the IC II intensifying screen, and Kodak processing was used.

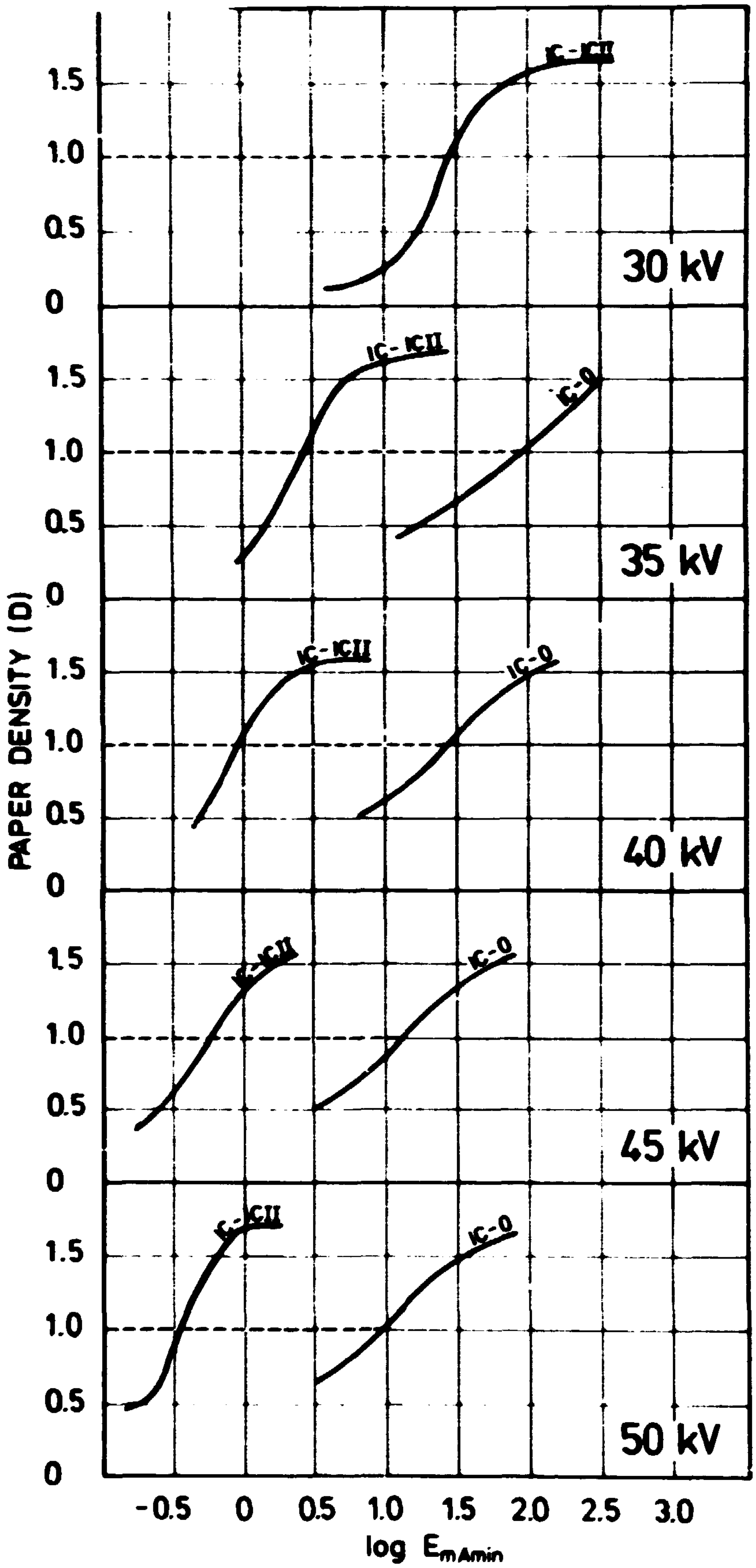

Fig. 24. Characteristic curves of the Agfa-Gevaert IC paper exposed without and with IC II intensifying screens at 30 to 50 kV.

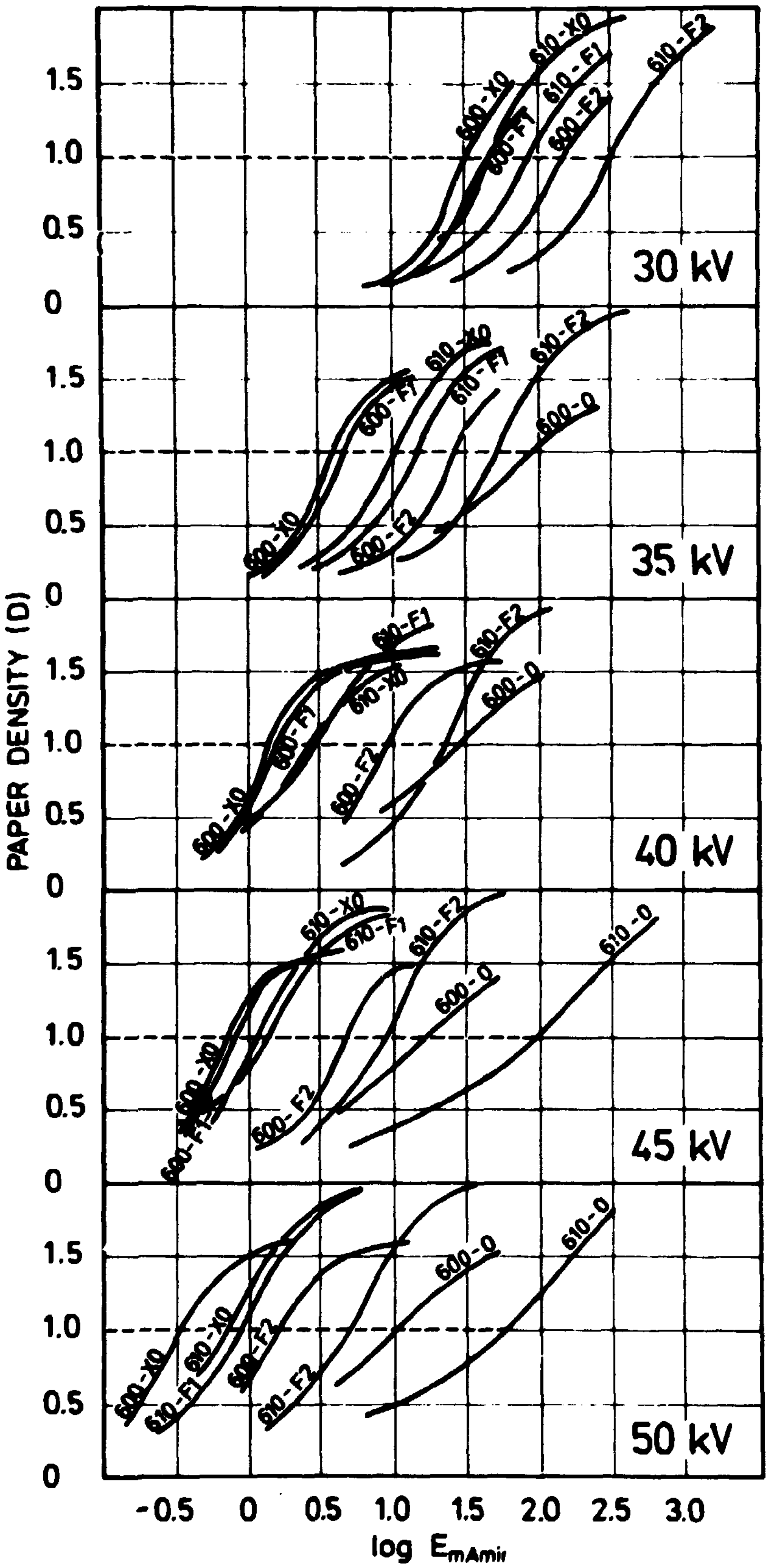

Fig. 25. Characteristic curves of the Kodak 600 and 610 paper exposed without and with XO, F1 and F2 intensifying screens at 30 to 50 kV.

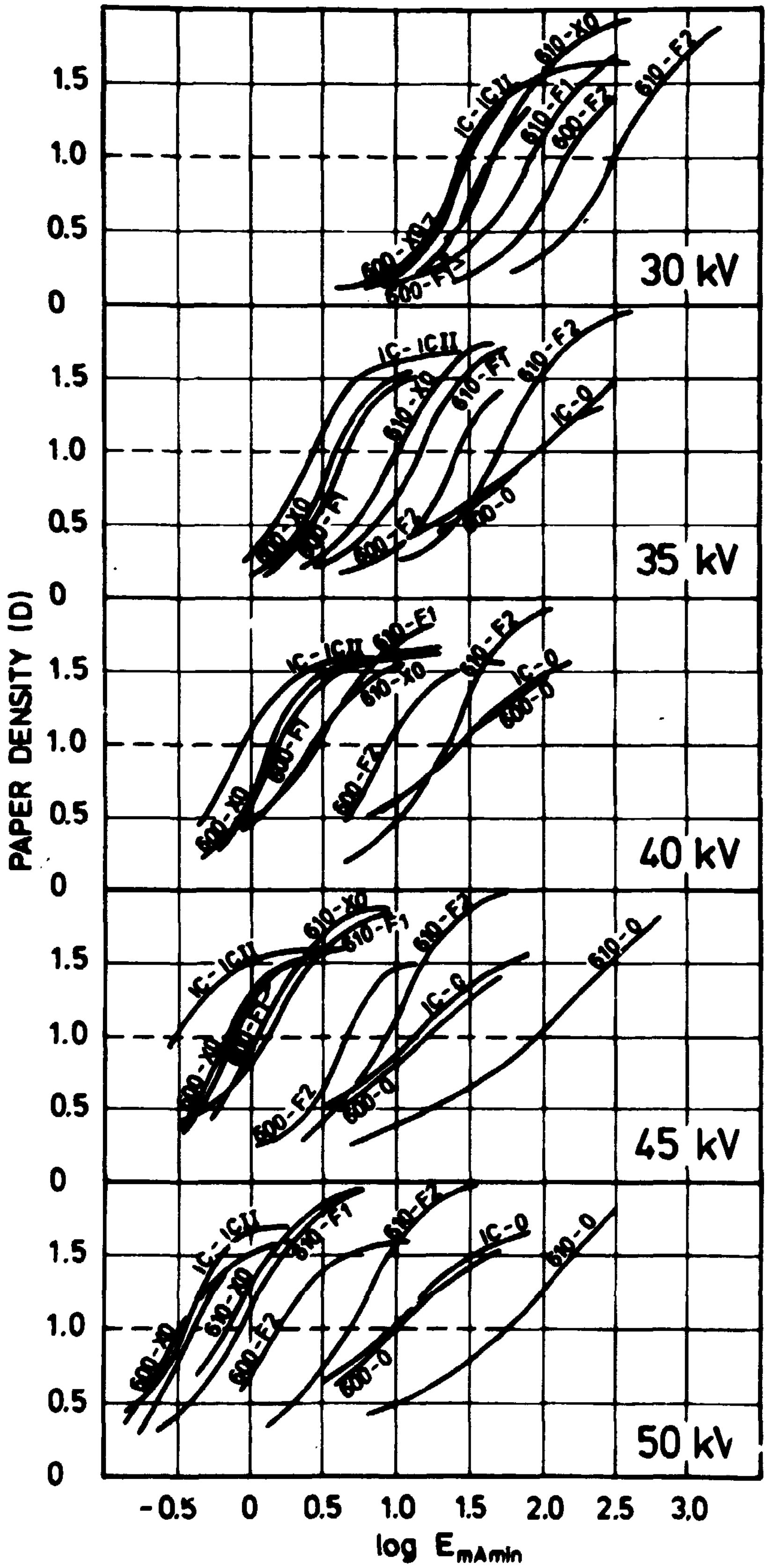

Fig. 26. Characteristic curves of the Agfa-Gevaert and Kodak at 30 to 50 kV.

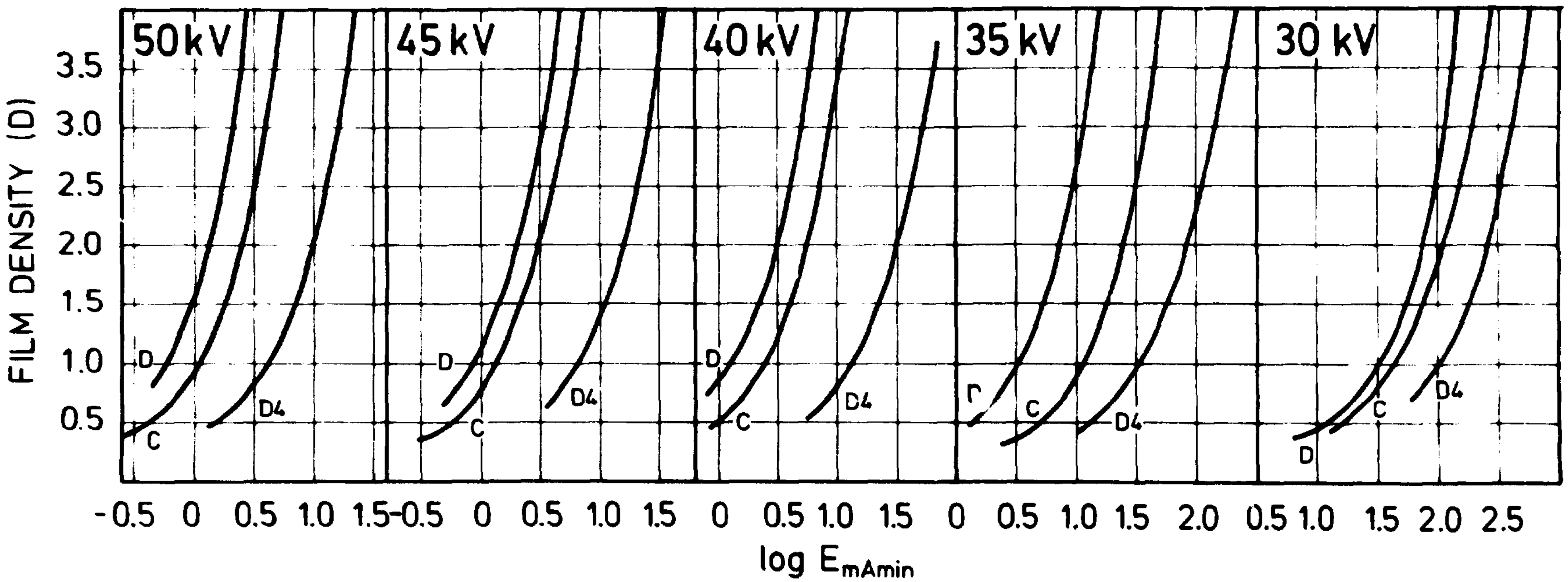

Fig. 27. Characteristic curves of the Agfa-Gevaert Structurix D4 and Kodak Industrex C and D films exposed without screens at 30 to 50 kV.

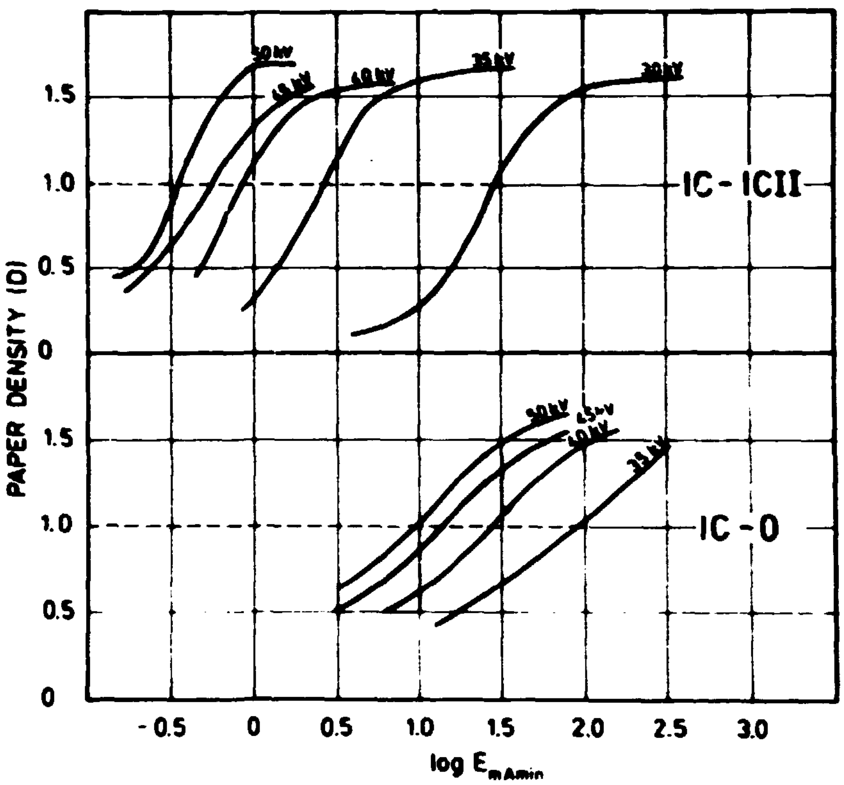

Fig. 28. Characteristic curves of the IC paper at 30 to 50 kV.

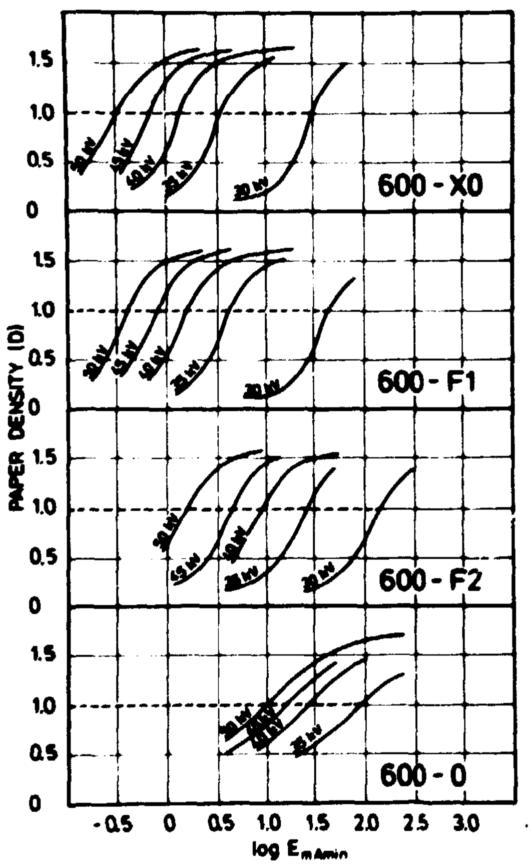

Fig. 29. Characteristic curves of the 600 paper at 30 to 50 kV.

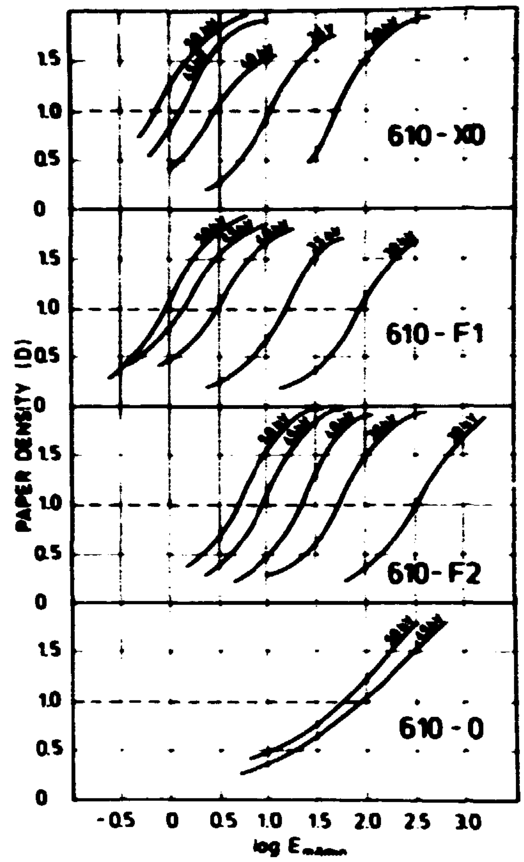

Fig. 30. Characteristic curves of the 610 paper at 30 to 50 kV.

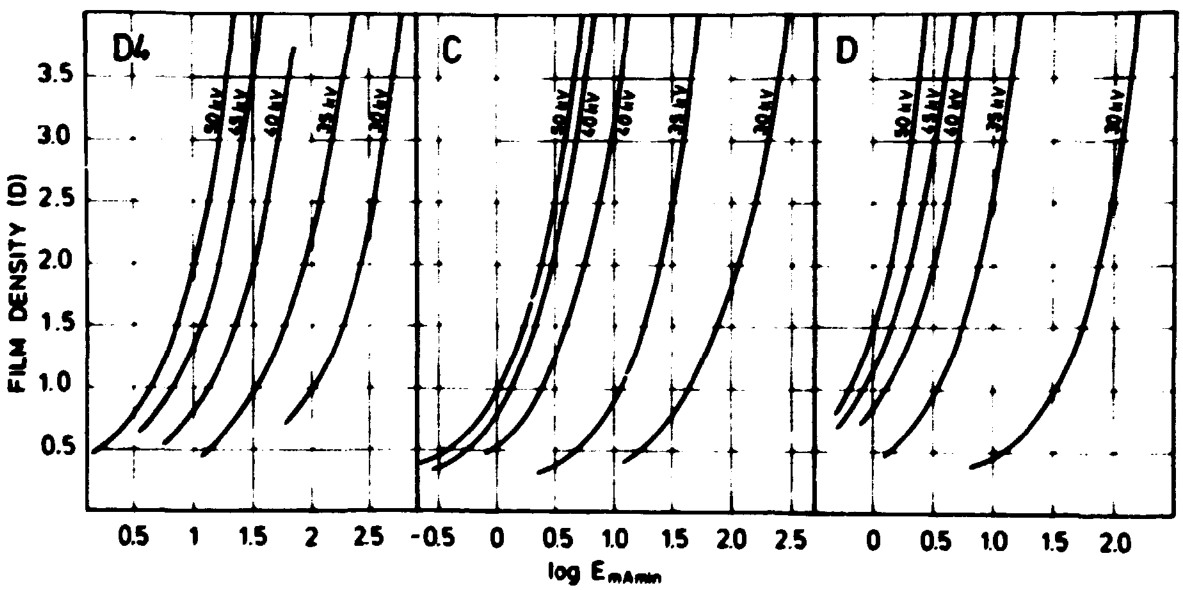

Fig. 31. Characteristic curves of the D4, C and D films at 30 to 50 kV.

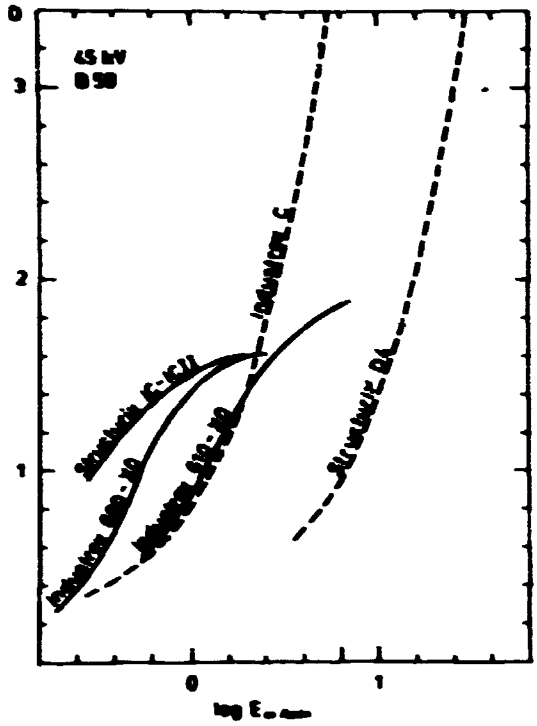

Fig. 32. Characteristic curves of radiographic paper and film at 45 kV.

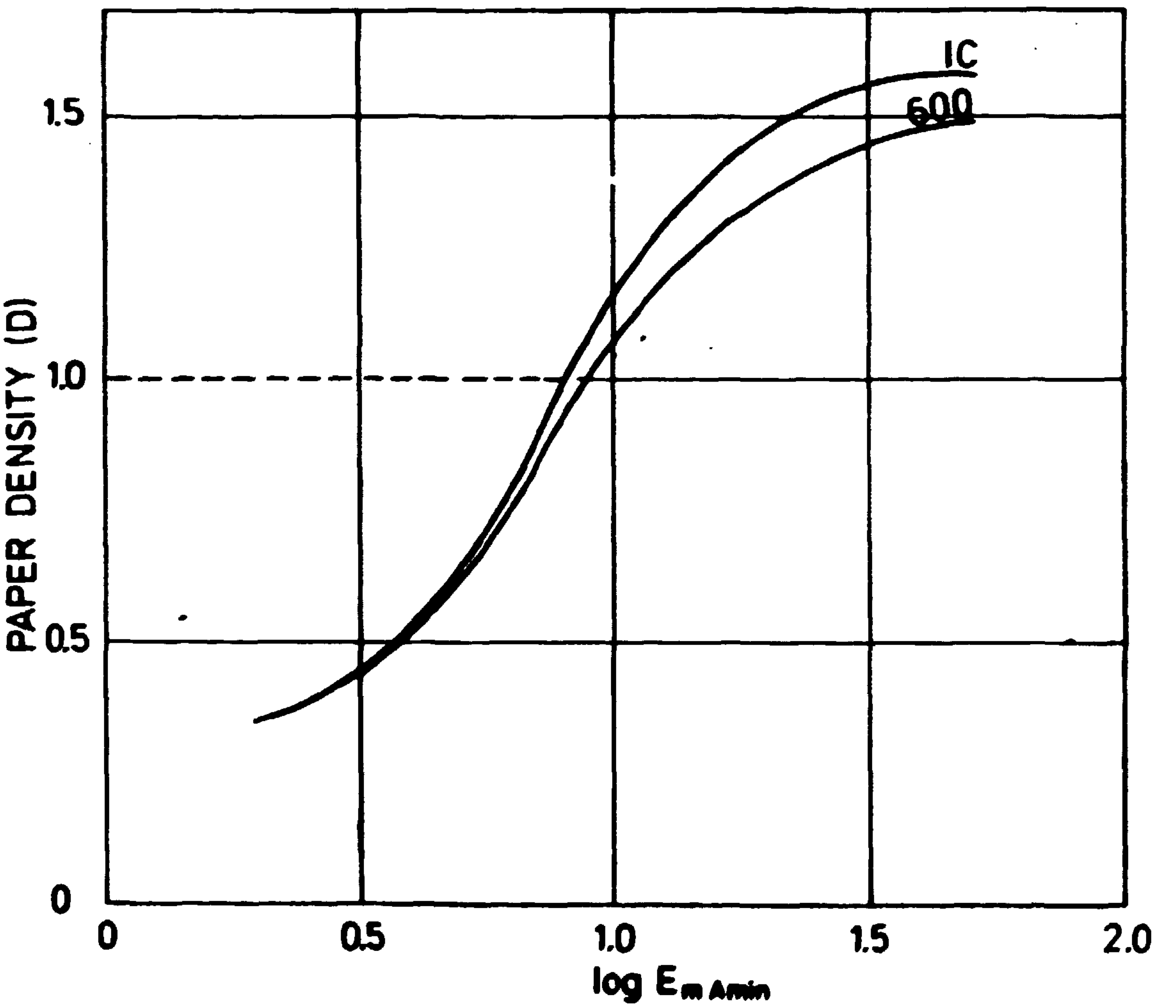

Fig. 33. Characteristic curves of the radiographic paper at 10 kV.

5.2. Intermediate voltage range

As mentioned before, exposure charts for aluminium were produced up to a thickness of 35 mm using the 50 kV X-ray machine. For thicker Al objects, an Andrex 180 kV, exposure charts for up to 70 mm of Al were produced.

To be able to compare the sensitometric properties of the radiographic paper in this voltage range, characteristic curves were produced at 100 kV using a 30 mm Al filter at the X-ray tube window. The results are shown in fig. 34, where also a curve for the Kodak Industrex C X-ray film is included (taken with 0.05 + 0.10 mm lead screens).

It was suggested in the literature that better quality paper radiographs can be obtained in this voltage range if a thin lead filter is used on the cassette. This was proved to be correct and therefore a 0.05 mm Pb filter was used both for the production of characteristic curves on the radiographic paper, as well as during all other experiments and in routine radiography.

Using the Andrex 300 kV X-ray machine, exposure charts were made for steel and radiogrphy carried out on the U/Al blocks[12). It was experimentally found that 30 mm of copper was roughly equivalent to 30 mm of U/Al alloy, and therefore 30 mm of Cu was used as a filter during the production of the characteristic curves shown on fig. 34. A 0.05 mm Pb filter was used on the cassette too.

In routine paper radiography of U/Al blocks, 150 kV was used, and for this voltage (and the Andrex 300 kV X-ray machine) characteristic curves were produced as shown on fig. 35. Only the 0.05 Pb filter was used on the cassette.

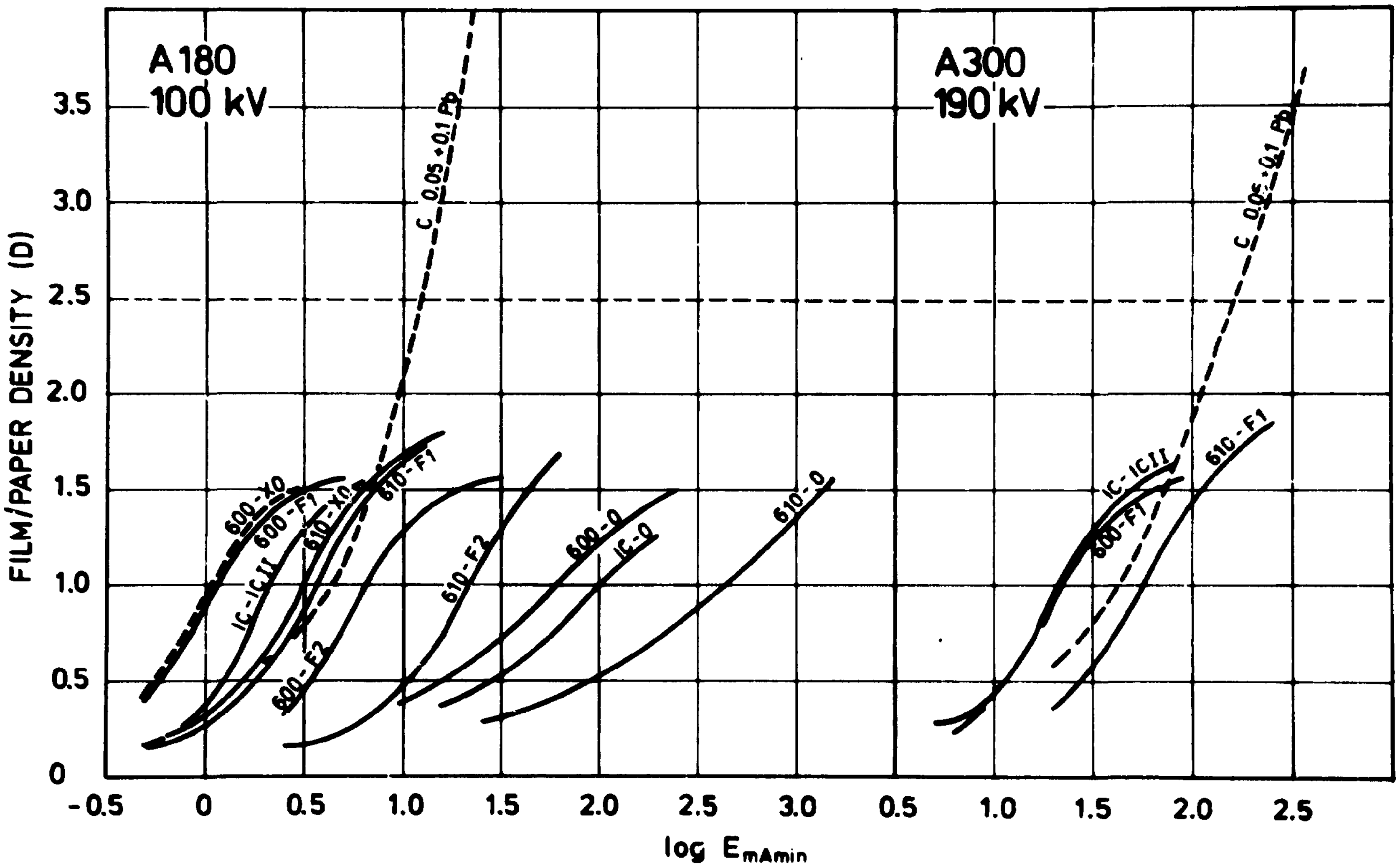

Fig. 34. Characteristic curves at 100 and 190 kV with 0.05 mm Pb filter on the cassette (30 mm Al at the X-ray tube for 100 kV and 20 mm Cu for 190 kV).

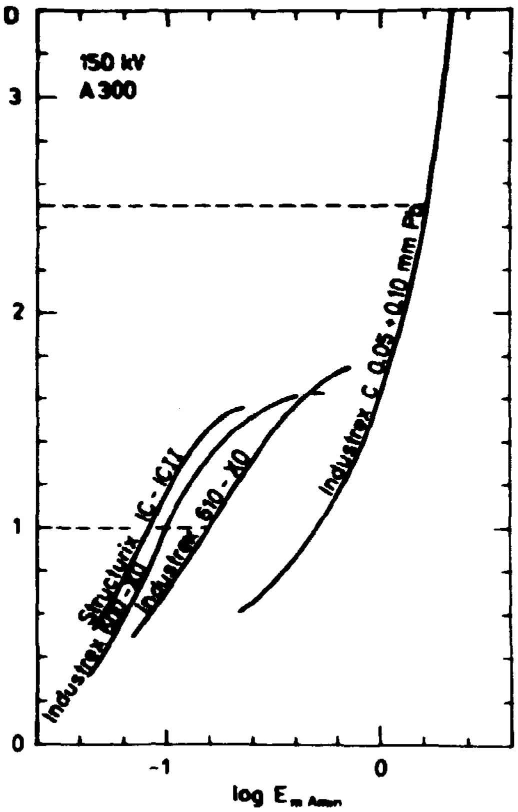

Fig. 35. Characteristic curves at 150 kV with 0.05 mm Pb filter on the cassette.

6. SPEED, CONTRAST AND EXPOSURE LATITUDE

From the characteristic curves presented in the preceding chapter 5, the relative speed, contrast and exposure latitude of various paper/screen combinations can be derived.

6.1. Relative Speed

All the characterestic curves presented in chapter 5 were produced by giving the optical density D as a function of the logarithm of exposures in mAmin at different voltages for a constant FFD = 1 m. From these curves the relative paper or film speed can be derived by comparing the exposures (in mAmin) necessary to obtain a constant density at each of the kilovoltages. For the sake of such a comparison, a paper density of $D_p = 1.0$ and a film density of $D_f = 2.5$ were chosen. Table 12 gives the esposures (in mAmin) necessary to reach $D_p = 1.0$ or $D_f = 2.5$ for different kilovoltages and paper screen combinations, as well as for different film brands. This table was computed for data obtained in the low voltage range.

Table 13 gives similar results for the intermediate voltage range.

From tables 12 and 13, intensification factors can be calculated for the different combinations of paper and screen. They are given in table 14 as a quotient between the exposures necessary to reach the same $D_p = 1$ density of the paper exposed without and with the intensifying screen.

As mentioned before, it was not possible to produce characteristic curves for the radiographic paper exposed without intensifying screens for the lowest voltages (30 kV for the IC and 600 paper and 30, 35 and 40 kV for the 610 paper) as well as for 150 and 190 kV, because the exposure times proved to be unacceptably long. Therefore data for these voltages are missing in tables 12, 13, and 14.

From tables 12 and 13 the relative speed can be calculated of different paper and screen combinations. In table 15 the results of such calculations are shown for radiographic paper used without and with intensifying screens. The slowest paper (Kodak 610) and the slowest screen (F2) were chosen as a reference speed of 1.0.

For the sake of comparison, the characteristic curves of X-ray films (D4, C and D) were also taken and the exposures necessary to reach the density $D_f = 2.5$ are listed in tables 12 and 13. In table 16 the relative speed is calculated for the radiographic paper and these three brands of X-ray films. Here the slowest film (D4) was taken as reference with a relative speed of 1.0.

Table 12

Exposures (in mAmin) necessary to reach $D_p = 1.0$ or $D_f = 2.5$ in the low voltage range (FFD = 1 m).

Screen	No screen						IC II	XO		F1		F2	
Paper or film	IC	600	610	D4	C	D	IC	600	610	600	610	600	610
30 kV	-	-	-	346.74	158.49	91.20	28.84	31.62	50.12	45.71	87.10	144.54	316,23
35 kV	87.10	39.81	-	114.82	31.62	9.12	2.75	3.47	10.47	4.07	15.85	26.30	54.95
40 kV	27.54	27.54	-	39.81	7.24	3.98	0.85	1.38	2.69	1.58	2.88	8.71	22.91
45 kV	13.49	15.85	91.20	21.58	3.80	2.51	0.56	0.71	1.26	0.83	1.32	4.47	8.91
50 kV	9.12	10.00	60.26	13.80	3.16	1.70	0.32	0.33	0.72	0.42	0.93	1.58	5.13

Table 13

Exposures (in mAmin) necessary to reach $D_p = 1.0$ or $D_f = 2.5$ in the intermediate voltage range (FFD = 1 m).

Screen	No screen			IC II	XO		F1		F2		0.05 + 0.10 Pb
Paper or film	IC	600	610	IC	600	610	600	610	600	610	C
100 kV	100.00	60.26	446.68	2.09	1.10	3.16	1.01	3.72	6.46	22.39	12.30
190 kV	-	-	-	20.89	-	-	21.88	56.23	-	-	158.49
150 kV	-	-	-	0.08	0.10	0.16	-	-	-	-	1.66

At 150 kV no filtration at the X-ray tube was used, whereas at 100 kV a 30 mm Al and at 190 kV a 20 mm Cu filter was used.

Table. 14. Intensification factors for different paper and screen combinations.

Screen	IC II	XO		F1		F2	
Paper	IC	600	610	600	610	600	610
30 kV	-	-	-	-	-	-	-
35 kV	31.67	11.47	-	9.81	-	1.51	-
40 kV	32.40	19.96	-	17.43	-	3.16	-
45 kV	24.09	22.32	72.38	19.10	69,09	3.55	10.24
50 kV	28.50	30.30	83.69	23.81	64.80	6.33	11.75
100 kV	47.86	10.44	141.35	11.37	120.08	1.18	19.95

Table 15

Relative speed of radiographic paper and screen.
(From characteristic curves).

Screen	No screen			IC II	X0		F1		F2	
Paper	IC	600	610	IC	600	610	600	610	600	610
30 kV	-	-	-	10.69	10.00	6.31	6.92	3.63	2.19	1
35 kV	-	-	-	19.98	15.84	5.25	13.50	3.47	2.09	1
40 kV	-	-	-	26.95	16.60	8.52	14.50	7.95	2.63	1
45 kV	6.76	5.75	1	28.78	15.91	7.07	10.73	6.75	1.99	1
50 kV	6.61	6.03	1	16.03	15.55	7.13	12.21	5.52	3.25	1
100 kV	4.47	7.41	1	10.71	20.35	7.09	22.17	6.02	3.47	1

Table 16

Relative speed of radiographic paper and X-ray film.
(From characteristic curves).

Screen	No Screen			IC II	X0		F1		F2	
Paper or film	D4	C	D	IC	600	610	600	610	600	610
30 kV	1	2.19	3.80	12.02	10.97	6.92	7.59	3.98	2.40	1.10
35 kV	1	3.63	12.59	41.75	33.09	10.97	28.21	7.24	4.37	2.09
40 kV	1	5.50	10.00	46.84	28.85	14.80	25.20	13.82	4.57	1.74
45 kV	1	5.63	8.52	38.18	30.11	16.97	25.76	16.20	4.78	2.40
50 kV	1	4.37	8.12	43.13	41.82	19.17	32.86	14.84	8.73	2.69
100 kV	-	0.05 + 0.40 % 1	-	5.89	11.18	3.89	12.18	3.31	1.90	0.55
190 kV	-	0.05 + 0.40 % 1	-	7.59	-	-	7.24	2.82	-	-
150 kV	-	1	-	20.75	16.60	10.38	-	-	-	-

6.2. Contrast

From the characteristic curves, paper or film contrast (γ) can be calculated. This was done by measuring the angle (α) of the tangent to the characteristic curve (as shown on fig. 36). The contrast was calculated as

$$\gamma = \mathrm{tg}\ \alpha.$$

Paper and film contrasts were calculated at different densities, and the results of these calculations are presented graphically on the following figures.

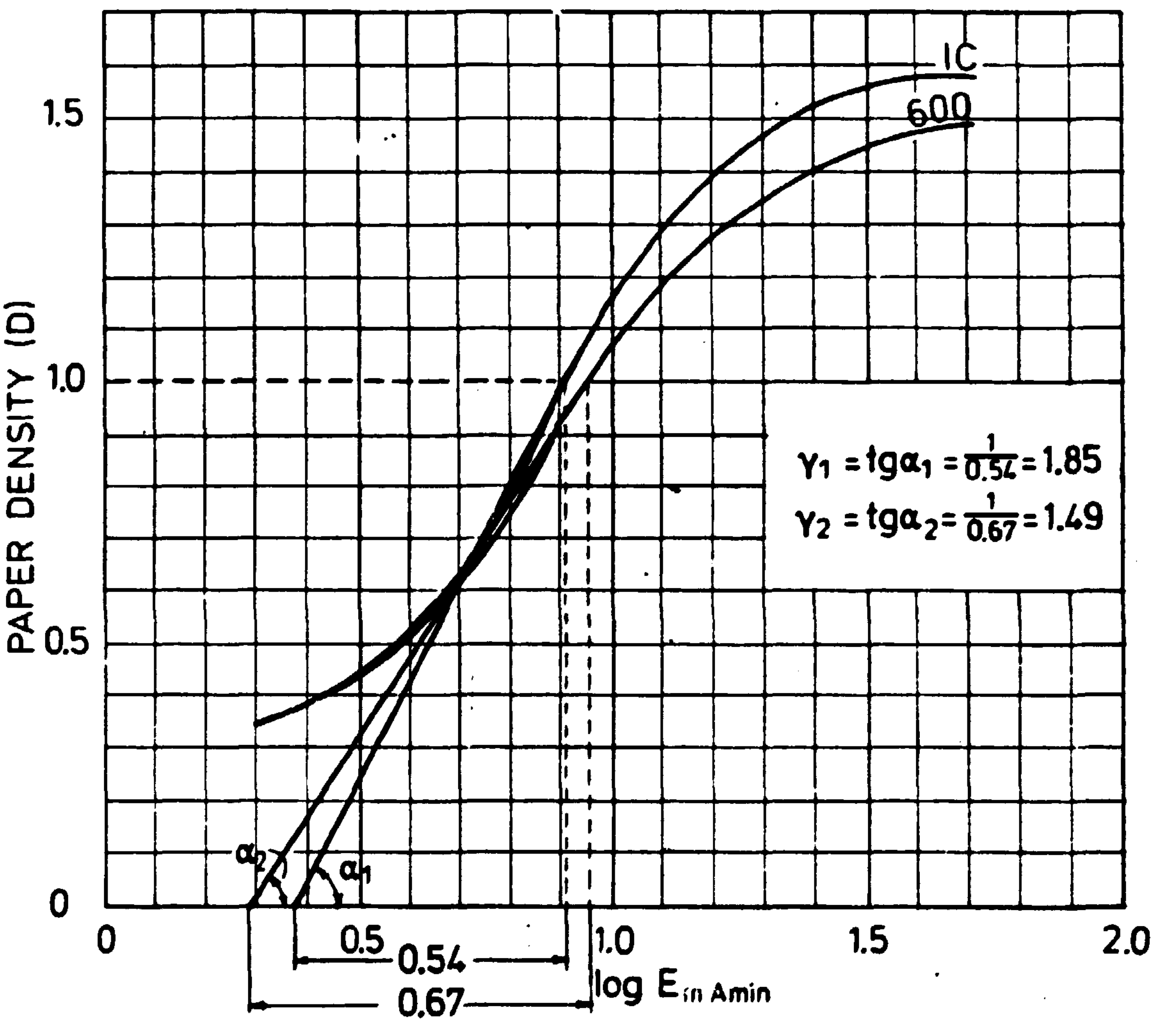

Fig. 36. Contrast calculated from the characteristic curves.

For the low voltage range, fig. 37 gives the contrast of the Agfa-Gevaert Structurix IC paper, exposed at voltages from 30 to 35 kV without and with ICII intensifying screen.

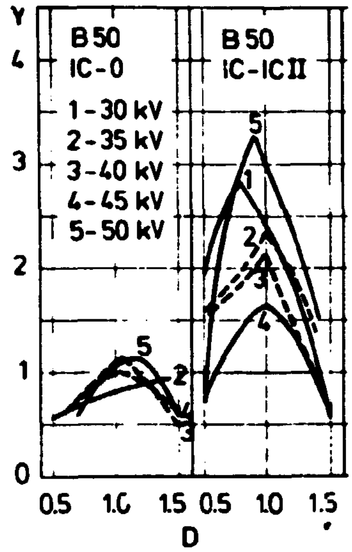

Fig. 37. Contrast of the Agfa-Gevaert Structurix IC paper at the low voltage range.

A similar set of contrast curves is shown on fig. 38 for the Kodak Industrex Instant 600 paper exposed at 30 to 50 kV without and with F2, F1 and X0 intensifying screens. The same is shown on fig. 39 for the 610 paper.

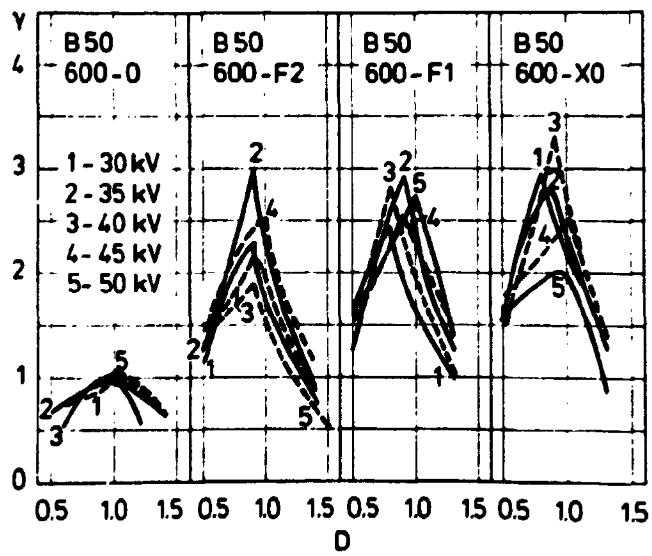

Fig. 38. Contrast of the Kodak Industrex Instant 600 paper at the low voltage range.

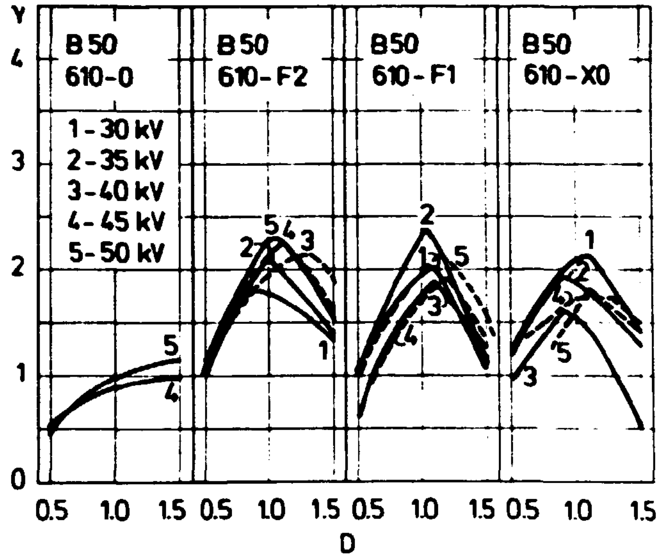

Fig. 39. As fig. 38, for the 610 paper.

In a similar way, the contrast of X-ray films exposed without intensifying screens in the low voltage range is shown on the following curves: on fig. 40 for the Agfa-Gevaert Structurix D4 film, and on fig. 41 and 42 for Kodak Industrex C and D films.

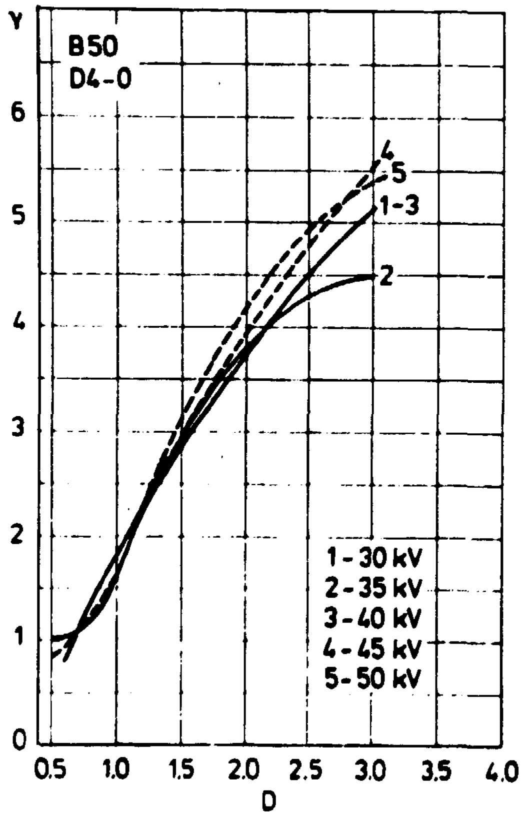

Fig. 40. As fig. 38, for the D4 film.

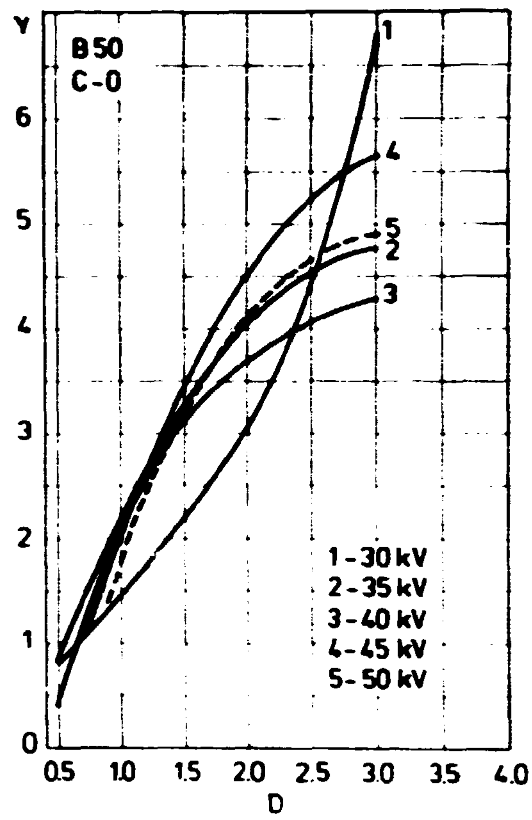

Fig. 41. As fig. 38, for the C film.

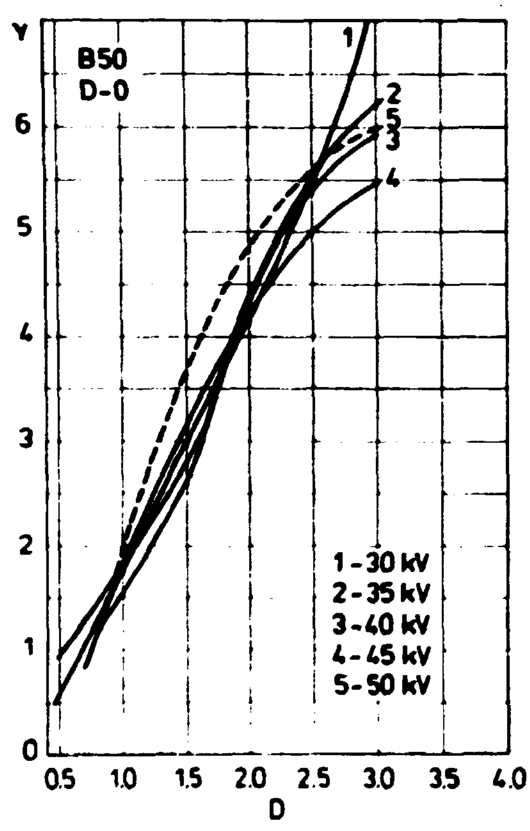

Fig. 42. As fig. 38, for the D film.

From the characteristic curves taken at 10 kV for the IC and 600 papers, the contrast was calculated and the results are shown on fig. 43.

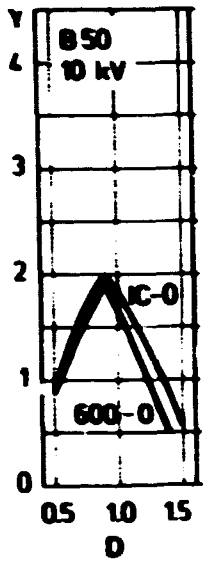

Fig. 43. Contrast of the IC paper at 10 kV.

In the intermediate voltage range, the IC paper was exposed at 100 kV and the corresponding contrast is shown on fig. 44. For the 600 and 610 papers exposed at 100 kV, the contrast is shown on fig. 45 and 46. Figure 47 shows the contrast of the C film at 100 kV.

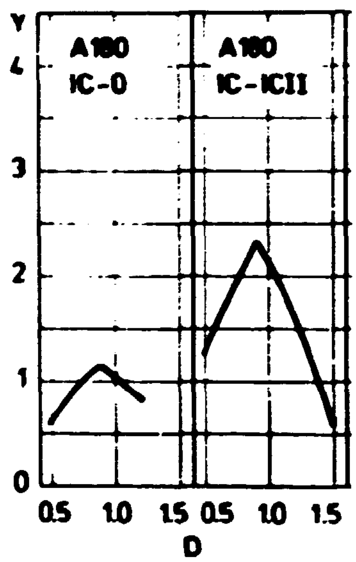

Fig. 44. Contrast of the IC paper at 100 kV.

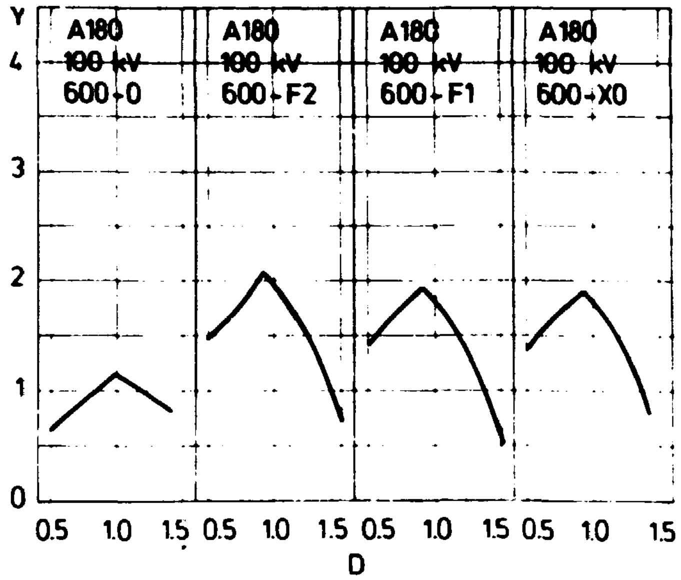

Fig. 45. As fig. 44, for the 600 paper.

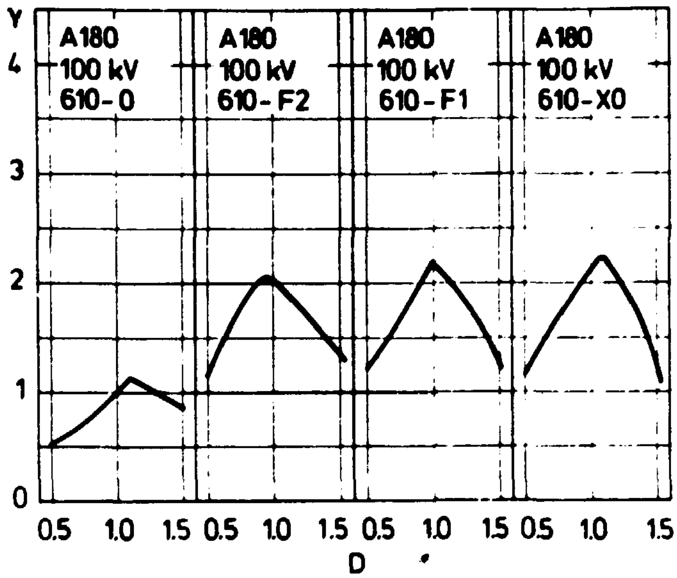

Fig. 46. As fig. 44, for the 610 paper.

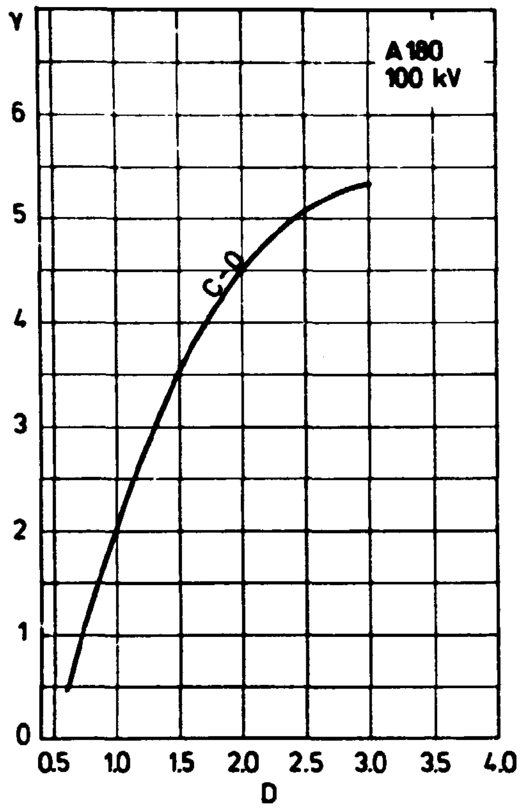

Fig. 47. As fig. 44, for the C film.

At 190 kV characteristic curves were produced for the IC-ICII and 600-F1 and 610-F1 paper/screen combinations, as well as for the C film exposed with 0.05 + 0.10 mm Pb screens. The contrast calculated from these curves is shown on fig. 48. Figure 49 shows the contrast at 150 kV for the IC-ICII, 600-X0 and 610-X0 paper/screen combinations, as well as for the C film with 0.05 + 0.1 mm Pb screens.

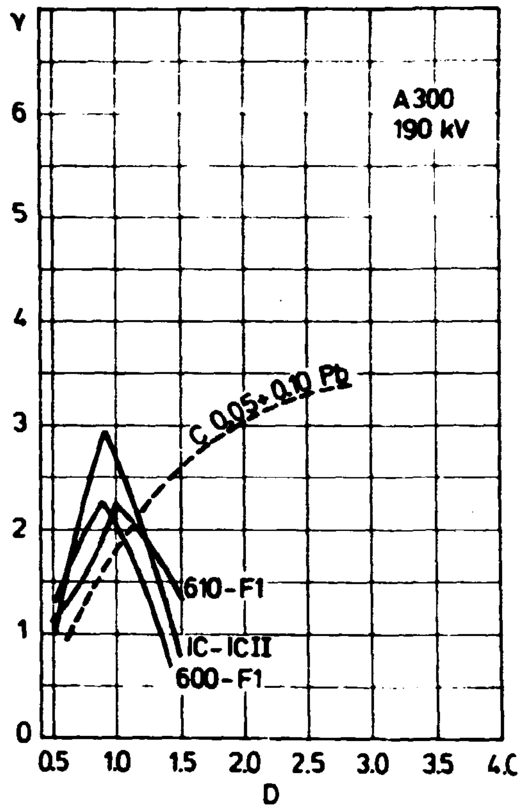

Fig. 48. Contrast of the IC, 600 and 610 paper at 190 kV.

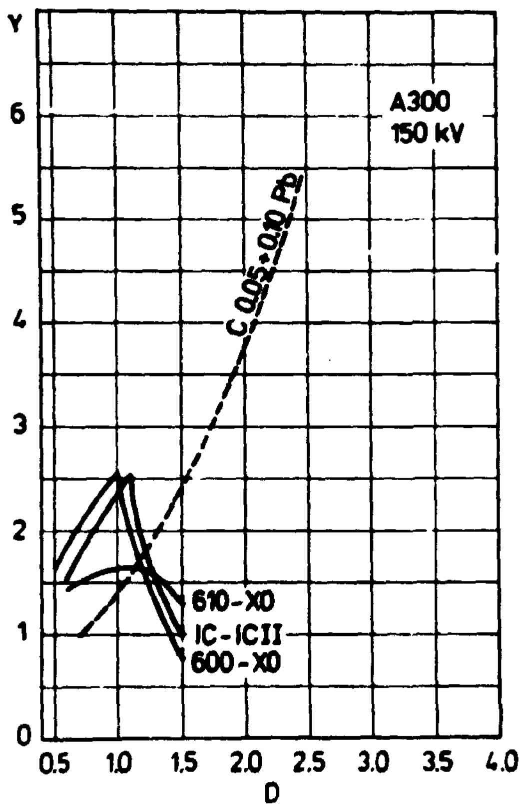

Fig. 49. As fig. 48, for 150 kV.

Exposure data for all the characteristic curves from which the above contrast curves were computed are given in table 11.

As can be seen from the contrast curves, the maximum contrast is reached for paper densities between 0.9 and 1.1. Therefore a paper density of $D_p = 1.0$ was chosen as reference density for calculating the relative paper speed in chapter 6.1 above. In most radiography standards, an X-ray film density of between 2.0 and 3.0 is required, therefore a film density of $D_f = 2.5$ was chosen as reference density in calculating the relative film speed.

From the contrast curves the maximum paper as well as the paper contrast at $D_p = 1.0$ and film contrast at $D_f = 2.5$ were calculated. These contrasts are tabulated in tables 17 and 18.

In these tables $\gamma_m = \gamma_{max}$ is the maximum contrast reached at paper density D_{γ_m}. The paper contrast at density $D_p = 1.0$ is marked as γ_{D_p}, whereas the film contrast at $D_f = 2.5$ is marked γ_{D_F}.

Table 17. Paper and film contrast in the low voltage range.

X-ray machine		Balteau B 50																						
kV		30				35				40				45				50				10		
Paper Film	Screen	γ_m	D_{γ_m}	γ_{D_p}	γ_{D_f}	γ_m	D_{γ_m}	γ_{D_p}	γ_{D_f}	γ_m	D_{γ_m}	γ_{D_p}	γ_{D_f}	γ_m	D_{γ_m}	γ_{D_p}	γ_{D_f}	γ_m	D_{γ_m}	γ_{D_p}	γ_{D_f}	γ_m	D_{γ_m}	γ_{D_p}
IC	0	-	-	-	-	0.9	1.4	0.8	-	1.1	1.0	1.1	-	1.0	1.0	1.0	-	1.1	1.1	1.1	-	2.0	0.9	1.9
IC	ICII	2.8	0.8	2.5	-	2.4	1.0	2.4	-	2.1	1.0	2.1	-	1.7	1.0	1.7	-	3.3	0.9	2.9	-	-	-	-
600	0	-	-	-	-	1.0	1.0	1.0	-	1.1	1.1	1.1	-	1.0	1.0	1.0	-	1.1	1.0	1.1	-	1.5	1.0	1.9
600	F2	2.3	0.9	1.7	-	3.0	0.9	2.2	-	2.1	0.9	2.0	-	1.5	1.0	1.5	-	1.9	1.0	1.9	-	-	-	-
600	F1	2.4	0.8	1.7	-	2.9	0.9	2.9	-	2.9	0.8	2.0	-	2.6	0.9	2.3	-	2.7	1.0	2.7	-	-	-	-
600	X0	2.9	0.8	2.3	-	2.5	0.9	2.4	-	3.3	0.9	2.7	-	2.5	1.0	2.5	-	2.0	1.0	2.0	-	-	-	-
610	0	-	-	-	-	-	-	-	-	-	-	-	-	1.0	1.6	0.9	-	1.2	1.8	1.0	-	-	-	-
610	F2	1.8	1.0	1.8	-	2.1	1.0	2.1	-	2.2	1.3	1.9	-	2.3	1.1	2.1	-	2.3	1.0	2.3	-	-	-	-
610	F1	2.0	1.1	2.0	-	2.5	1.0	2.5	-	1.9	1.1	1.6	-	1.9	1.2	1.7	-	2.1	1.1	2.0	-	-	-	-
610	X0	2.1	1.1	2.1	-	2.0	0.9	1.9	-	1.6	0.9	1.6	-	1.7	1.0	1.7	-	1.8	1.1	1.6	-	-	-	-
D4	0	-	-	-	4.5	-	-	-	4.2	-	-	-	4.5	-	-	-	4.7	-	-	-	4.9	-	-	-
C	0	-	-	-	4.3	-	-	-	4.5	-	-	-	4.0	-	-	-	5.2	-	-	-	4.6	-	-	-
D	0	-	-	-	5.7	-	-	-	5.7	-	-	-	5.3	-	-	-	4.5	-	-	-	5.4	-	-	-

Table 18. Paper and film contrast in the intermediate voltage range.

X-ray machine		Andrex A180				Andrex A300							
kV		100				190				150			
Paper Film	Screen	γ_m	D_{γ_m}	γ_{D_p}	γ_{D_f}	γ_m	D_{γ_m}	γ_{D_p}	γ_{D_f}	γ_m	D_{γ_m}	γ_{D_p}	γ_{D_f}
IC	0	1.2	0.9	1.1	-	-	-	-	-	-	-	-	-
IC	ICII	2.3	0.9	2.2	-	3.0	0.9	2.8	-	2.6	1.1	2.2	-
600	0	1.1	1.0	1.1	-	-	-	-	-	-	-	-	-
600	F2	2.1	0.9	2.0	-	-	-	-	-	-	-	-	-
600	F1	1.9	0.9	1.9	-	2.3	0.9	2.1	-	-	-	-	-
600	X0	1.9	0.9	1.7	-	-	-	-	-	2.6	1.0	2.6	-
610	0	1.1	1.1	1.0	-	-	-	-	-	-	-	-	-
610	F2	2.1	1.0	2.1	-	-	-	-	-	-	-	-	-
610	F1	2.2	1.0	2.2	-	2.3	1.0	2.3	-	-	-	-	-
610	X0	2.2	1.1	2.1	-	-	-	-	-	1.7	0.9	1.6	-
C	0.05+0.1Pb	-	-	-	5.1	-	-	-	3.1	-	-	-	5.7

6.3. Exposure latitude

The relation between the maximum and minimum exposures that is acceptable for a certain radiographic paper or film is called the exposure latitude. For both the X-ray film and the radiographic paper, the minimum exposure is limited by the minimum contrast below which the radiographic quality will be inacceptably low. Density $D_{min} = 0.5$ can be considered as minimum density, both for the radiographic paper as well as for X-ray film. The maximum density limits for paper and for film differ. The contrast of the industrial X-ray film increases with its density. Therefore the maximum density will be limited only by the practical possibilities of reading high film densities. Here $D_{max} = 3.5$ can be considered as the practical upper limit for X-ray films. For the radiographic paper, contrast decreases

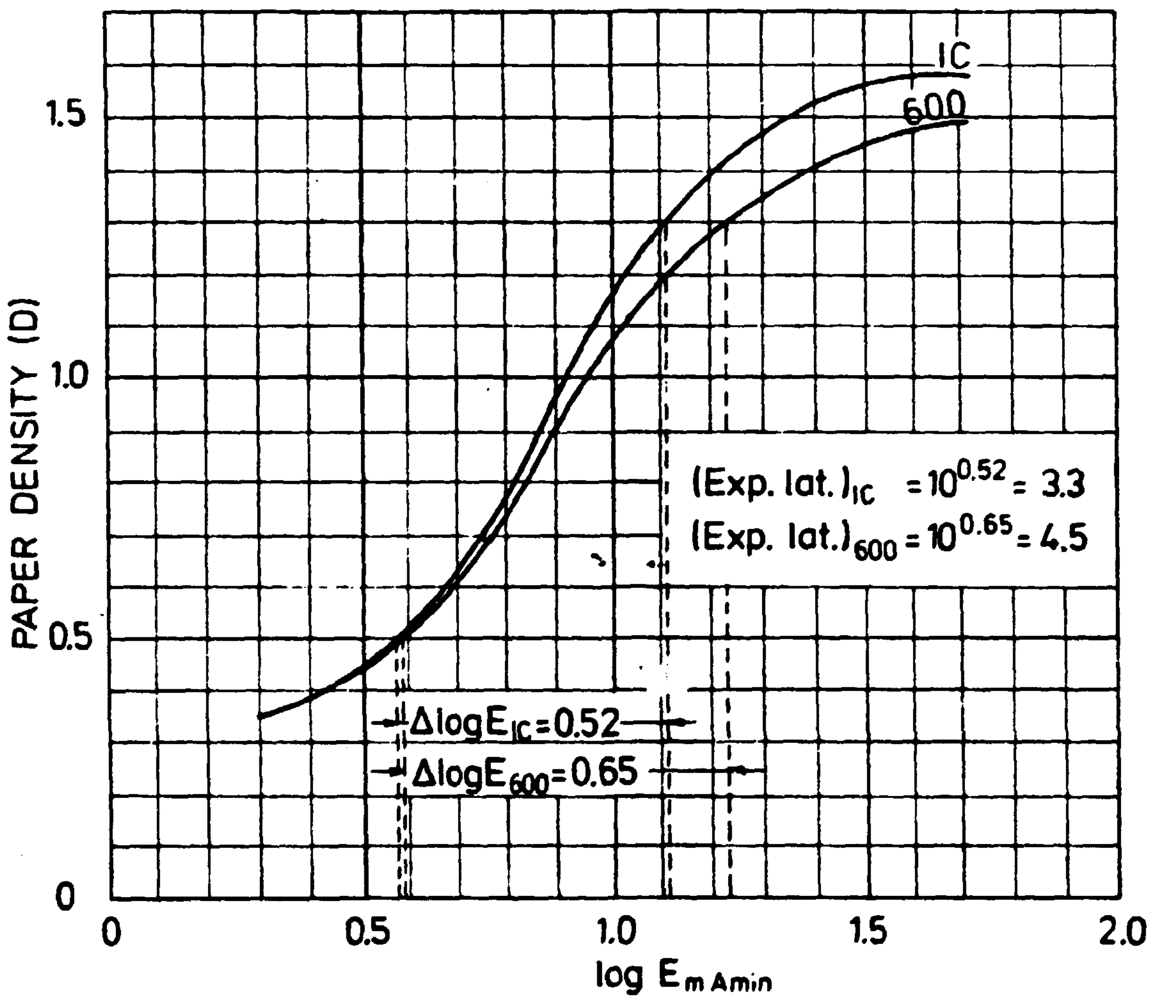

Fig. 50. Calculation of exposure latitude from the characteristic curves.

Table 19. Exposure latitude (E.L.) in the low voltage range.

X-ray machine		Balteau B 50											
kV		30		35		40		45		50		10	
Paper Film	Screen	D	E.L.	D	E.L.	D	E.L.	D	E.L.	D	E.L.	D	E.L.
IC	0	-	-	0.5-1.3	12.0	0.5-1.3	8.9	0.5-1.3	9.5	0.7-1.3	4.6	0.5-1.3	3.3
IC	IC II	0.5-1.3	2.8	0.5-1.3	2.8	0.5-1.3	2.9	0.5-1.3	4.0	0.5-1.3	2.5	-	-
600	0	-	-	0.5-1.3	11.2	0.6-1.3	5.8	0.5-1.3	9.1	0.7-1.3	4.7	0.5-1.3	4.5
600	F2	0.5-1.3	3.3	0.5-1.3	3.0	0.5-1.3	3.1	0.5-1.3	2.8	0.6-1.3	5.0	-	-
600	F1	0.5-1.3	2.9	0.5-1.3	2.6	0.5-1.3	2.7	0.5-1.3	2.6	0.5-1.3	2.5	-	-
600	XO	0.5-1.3	2.3	0.5-1.3	2.6	0.5-1.3	2.2	0.5-1.3	2.4	0.5-1.3	3.2	-	-
610	0	-	-	-	-	-	-	0.5-1.3	10.7	0.5-1.3	10.5	-	-
610	F2	0.5-1.3	3.5	0.5-1.3	3.2	0.5-1.3	3.0	0.5-1.3	4.0	0.5-1.3	4.6	-	-
610	F1	0.5-1.3	3.2	0.5-1.3	2.8	0.5-1.3	4.2	0.5-1.3	4.2	0.5-1.3	3.2	-	-
610	XO	0.5-1.3	2.6	0.5-1.3	3.1	0.5-1.3	4.0	0.6-1.3	2.6	0.8-1.3	1.9	-	-
D4	0	0.8-3.5	6.6	0.5-3.5	13.8	0.5-3.5	11.7	0.7-3.5	7.6	0.5-3.5	12.3	-	-
C	0	0.5-3.5	14.5	0.5-3.5	8.5	0.5-3.5	10.5	0.5-3.5	10.7	0.5-3.5	11.5	-	-
D	0	0.5-3.5	11.5	0.5-3.5	9.8	0.8-3.5	6.6	0.7-3.5	7.9	0.8-3.5	5.4	-	-

beyond a certain density (as was shown in the previous chapter). Therefore D_{max} = 1.3 can here be considered as the upper limit for paper density.

Thus, in calculating exposure latitude, densities between 0.5 and 3.5 are taken into consideration for X-ray films, whereas for the radiographic paper they are 0.5 and 1.3.

Figure 50 shows how the exposure latitude was calculated for the IC and 600 papers exposed at 10 kV without intensifying screens. The results of similar calculations for different paper/screen combinations and X-ray film are shown in tables 19 and 20.

Table 20. Exposure latitude (E.L.) in the intermediate voltage range.

X-ray machine		Andrex A180		Andrex A 300			
kV		100		190		150	
Paper Film	Screen	D	E.L.	D	E.L.	D	E.L.
IC	0	0.5-1.3	7.4	-	-	-	-
IC	IC II	0.5-1.3	2.6	0.5-1.3	2.8	0.5-1.3	2.8
600	0	0.5-1.3	7.9	-	-	-	-
600	F2	0.5-1.3	3.0	-	-	-	-
600	F1	0.5-1.3	3.2	0.5-1.3	3.2	-	-
600	XO	0.5-1.3	3.0	-	-	0.5-1.3	2.8
610	0	0.5-1.3	9.2	-	-	-	-
610	F2	0.5-1.3	3.0	-	-	-	-
610	F1	0.5-1.3	3.0	0.5-1.3	3.0	-	-
610	XO	0.5-1.3	2.9	-	-	0.5-1.3	3.5
C	0.05+0.1 Pb	0.6-3.5	9.5	0.6-3.5	16.2	0.6-3.4	8.7

7. QUALITY OF THE RADIOGRAPHIC IMAGE

As mentioned before, standard ISO IQIs could not be used to control the quality of the U/Al fuel plates or the U/Al blocks. They were, however, used to assess the radiographic quality of aluminium and steel radiographs.

7.1. Radiographic quality of U/Al plates

A MTR fuel plate is composed of an U/Al core, rolled down from a 30 mm block to a 0.54 mm plate, sandwiched between two 0.46 mm Al plates. Because of the composition of such a plate, as well as its thickness, it is impossible to check its radiographic quality by using standard IQIs. Therefore another approach had to be taken to solve the problem of fuel plate radiographic quality.

For this purpose the radiographic contrast of an Al step wedge was used for the assessment of the quality of the radiograph of a fuel plate. (This method is described in detail in 12).

To be able to choose the correct thickness of the Al step wedge, it was necessary to determine the aluminium equivalent of the fuel plate. This was done in the following way.

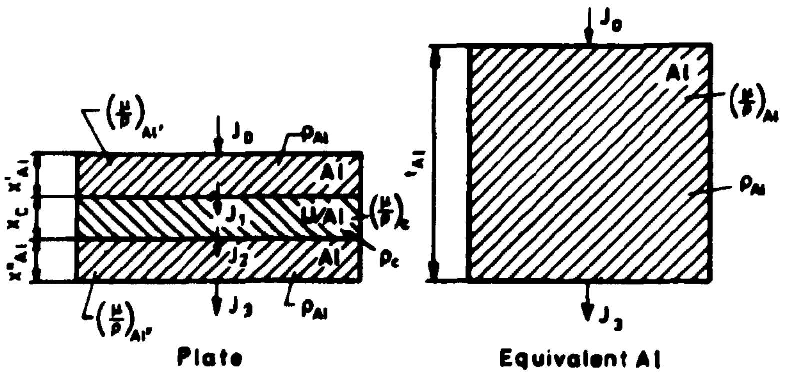

Fig. 51. Aluminium equivalent of an U/Al MTR fuel plate.

Figure 51 shows a cross section of a sandwiched MTR fuel plate in which $x'_{Al} = x''_{Al} = 0.46$ mm is the thickness of the two Al plates between which the $x_c = 0.54$ mm U/Al core is sandwiched. During radiography, radiation of intensity J_o impinges on the upper part of the plate. After passing through the upper

Al plate, this intensity is reduced to J_1. Leaving the U/Al core, the radiation intensity is reduced to J_2, and when it finally leaves the plate the radiation of original intensity J_o has been attenuated to J_3.

The equivalent Al thickness of the plate can be defined as the thickness t_{Al} that will attenuate the original radiation intensity to that of J_3 (as in the case of the MTR fuel plate). This can be expressed as follows:

$$t_{Al} = \frac{\left[(\frac{\mu}{\rho})_{Al} \cdot X'_{Al} + (\frac{\mu}{\rho})_{Al} \cdot X''_{Al}\right] \rho_{Al} + (\frac{\mu}{\rho})_c \, \rho_c X_c}{(\frac{\mu}{\rho})_{Al} \rho_{Al}}$$

where μ/ρ are the mass attenuation coefficients of the radiation and ρ are densities of the attenuating material.

As all the attenuation coefficients depend on the quality of radiation , so does the equivalent Al thickness, t_{Al}. The equation cannot be solved theoretically because the quality of radiation (energy) from the first Al-plate, as well as from the U/Al core, is unknown. In practice, the Al equivalent was determined by taking a radiograph of a plate together with two strips of Al of known thickness. The plate was put between these two Al strips, the thickness of which was chosen so as to lie a little above and below the estimated Al equivalent of the plate under examination.

The radiographs of the plate were scanned with a densitometer at 12 lines evenly spaced across the picture of the plate and the Al strips. Thereafter an average plate film or paper density was calculated (using a planimeter). This average density of each scan was compared with the densities under the Al strips and from this an average Al equivalent was computed for each scan. Finally, from all the 12 scans made for each plate radiograph, the mean value of the Al equivalent was calculated.

From the same scans, maximum and minimum Al equivalents for a particular plate could also be computed.

The results obtained by this method for different X-ray machines at various kilovoltages are shown in 12).

For a typical MTR plate, which is normally radiographed at 45 kV, the Al equivalents are shown in table 21[23].

Table 21. Al equivalents of a typical MTR plate radiographed at 45 kV.

X-ray Film	X-ray Paper	Intensifying screens	Al equivalents - mm Al Maximum	Average	Minimum
D4	-	None	5.75	5.41	5.09
-	610	XO	5.81	5.35	5.12
-	IC	IC II	5.88	5.49	5.21

The density scanning arrangement for paper is shown and described in 12), and for films in 21) and 22). In both densitometers an aperture of Ø 1.6 mm was used.

The above results show very good agreement between measurements on film and paper, especially when taking into account the inaccuracy of the scanning arrangement itself, which did not quarantee that the scans of different radiographs could be made exactly across the same line on the plate.

Before producing radiographs of Al step wedges at different kilovoltages, the thickness ranges of the step wedges have to be chosen in accordance with the Al equivalents found in 12). Table 22 gives these equivalents for voltages from 30 to 50 kV.

Table 22. Al equivalents of an MTR U/Al fuel plate measured from the densitometric scans across the radiographic picture of the plate.

X-ray apparatus	kV	Thickness of Al strips (mm) D4	XO/IC	D4	XO/IC	Average Al equivalent from 12 transverse scans (mm) D4	XO	IC
Balteau 50	50	4.5	4.5	6.5	6.5	5,60	5.61	5.61
	45	4.5	4.5	6.5	6.5	5.41	5.35	5.49
	40	4.5	4.5	6.0	6.0	5.16	5.30	5.50
	35	4.0	4.5	5.5	5.5	4.88	4.94	5.21
	30	3.5	4.0	4.5	4.5	3.85	4.06	4.41

As can be seen, the Al equivalents vary with radiation energy. Therefore at 30 kV an Al step wedge ranging from 4 to 5 mm (in 0.1 mm increments) was used, whereas for voltages from 35 to 50 kV a step wedge from 5 to 6 mm Al was used.

After taking radiographs of these step wedges, paper or film densities were measured under the 11 steps. These densities were next divided by the density measured under the 4.5 mm (for 30 kV) or under the 5.5 mm Al step (for other voltages). The results of these calculations are shown on the following figures. Exposures were chosen in such a way as to reach a density of about $D_p = 1$ for paper and $D_f = 2.5$ for film measured under the 4.5 or 5.5 mm Al steps.

Figure 52 shows the density contrast under the Al step wedge for the Agfa-Gevaert Structurix IC paper, while figs. 53 and 54 give similar curves for the Kodak Industrex Instant 600 and 610 papers. Finally, fig. 55 shows results for X-ray films (Agfa-Gevaert Structurix D4 and Kodak Industrex C and D).

To be able to directly compare the density contrast of the Agfa-Gevaert and Kodak paper on figs. 56 and 57, the density contrast of these papers is reproduced. On figs. 58 and 59 direct comparison of the Kodak 600 and 610 paper is made, while fig. 60 gives a comparison for the X-ray films (D4, C and D).

In table 23 the results of density contrast measurements are summarized. The absolute density difference is given as measured under the thinnest and thickest Al steps (thickness difference of 1.0 mm Al), as well as the per cent density difference in relation to the middle Al step (4.5 mm Al at 30 kV and 5.5 mm Al at 35 to 50 kV).

In the routine control of the quality of the MTR fuel plates, 45 kV is used. Although a better density contrast can be reached at lower kilovoltages, 45 kV was chosen because at this voltage not only can the homogeneity of uranium distribution in the plate be assessed, but also the position of the core in the plate.

For the assessment of the radiographic quality of U/Al plates, an Al step wedge consiting of three steps: 5.0, 5.5 and 6.0 mm (corresponding roughly to the minimum, average and maximum expected Al equivalents) was chosen. This step wedge was radiographed at 45 kV to give paper densities of about $D_p = 1$ under the 5.5 mm step or $D_f = 2.5$ for X-ray film. Thereafter densities under the three steps were measured and the per cent density difference was calculated as follows:

$$\Delta D_{\%} = \frac{D_{5.0} - D_{6.0}}{D_{5.5}}\,100.$$

Table 23

Absolute and per cent density contrast

Paper Film	Screen	Density gradient at 30 kV		35 kV		40 kV		45 kV		50 kV	
		ΔD	ΔD %	ΔD	ΔD %	ΔD	ΔD %	ΔD	ΔD %	ΔD	ΔD %
IC	O	-	-	-	-	0.22	22.6	0.18	15.8	0.12	14.6
IC	IC II	0.53	57.6	0.36	32.4	0.30	35.3	0.31	28.7	0.24	25.5
600	0	-	-	-	-	0.14	13.1	0.14	14.3	0.16	16.7
600	F2	0.60	58.8	0.42	37.2	0.31	31.0	0.36	36.4	0.25	25.3
600	F1	0.75	78.4	0.47	49.5	0.33	33.0	0.31	32.3	0.29	28.4
600	XO	0.69	63.9	0.48	48.5	0.41	41.0	0.37	34.9	0.31	30.7
610	0	-	-	-	-	-	-	0.12	13.6	0.11	12.2
610	F2	0.60	66.7	0.40	44.0	0.29	31.9	0.23	23.0	0.20	20.0
610	F1	0.59	59.6	0.42	41.6	0.24	25.8	0.18	17.8	0.15	15.8
610	XO	0.55	53.9	0.36	34.0	0.28	31.8	0.26	25.5	0.21	21.0
D4	0	1.70	62.0	0.92	40.9	0.62	23.2	0.36	14.0	0.57	23.0
C	0	0.87	28.1	0.24	7.2	0.75	28.7	0.22	11.5	0.80	25.6
D	0	0.90	35.8	1.80	65.3	0.89	32.0	1.10	45.5	0.99	45.5

Table 24 gives the results obtained by this method for X-ray film and paper[24)]

Table 24

Per cent density differences at 45 kV

X-ray Film	X-ray Paper	Intensifying Screens	Per cent density difference $\Delta D_{\%}$
D4	-	None	23.2
C	-	None	27.0
-	610	XO	25.0
-	IC	IC II	28.4

This per cent density difference, which is a measure for radiographic contrast, was adopted for the assessment of the quality of MTR plate radiographs. It was required that $\Delta D_{\%} \geq 25\%$.

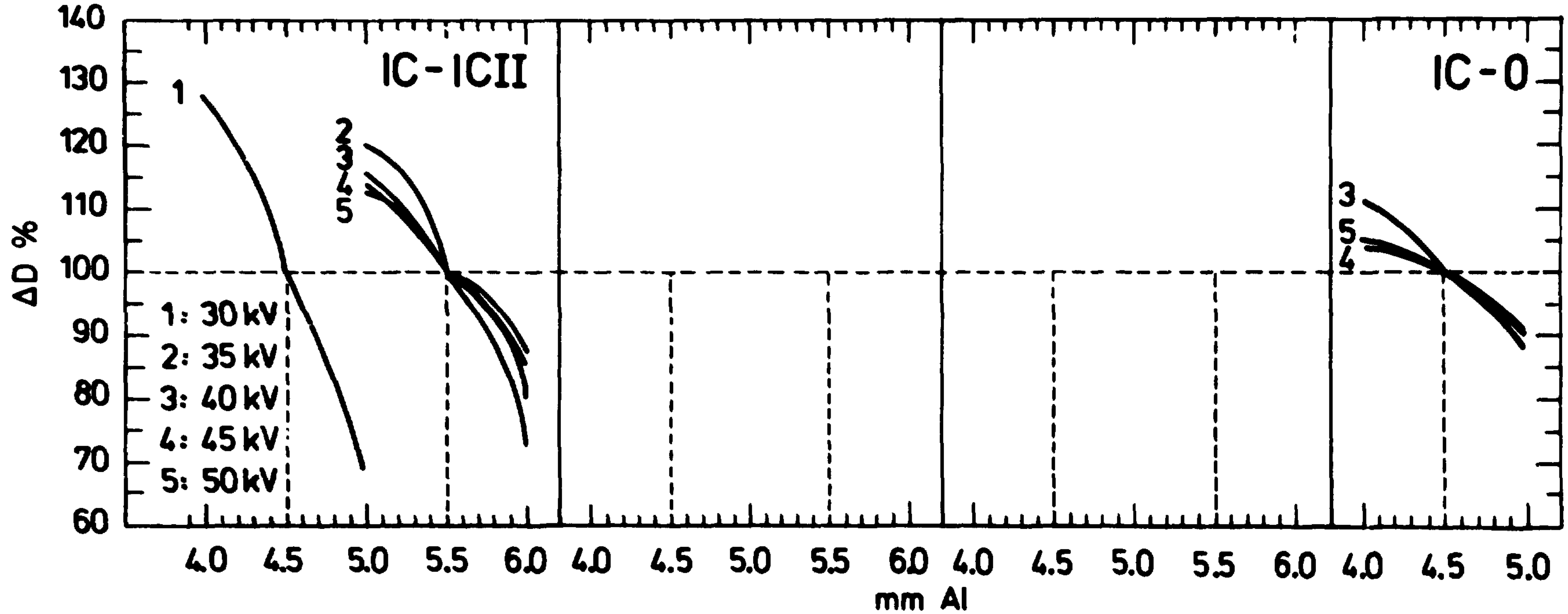

Fig. 52. Density contrast under Al step wedge for IC paper.

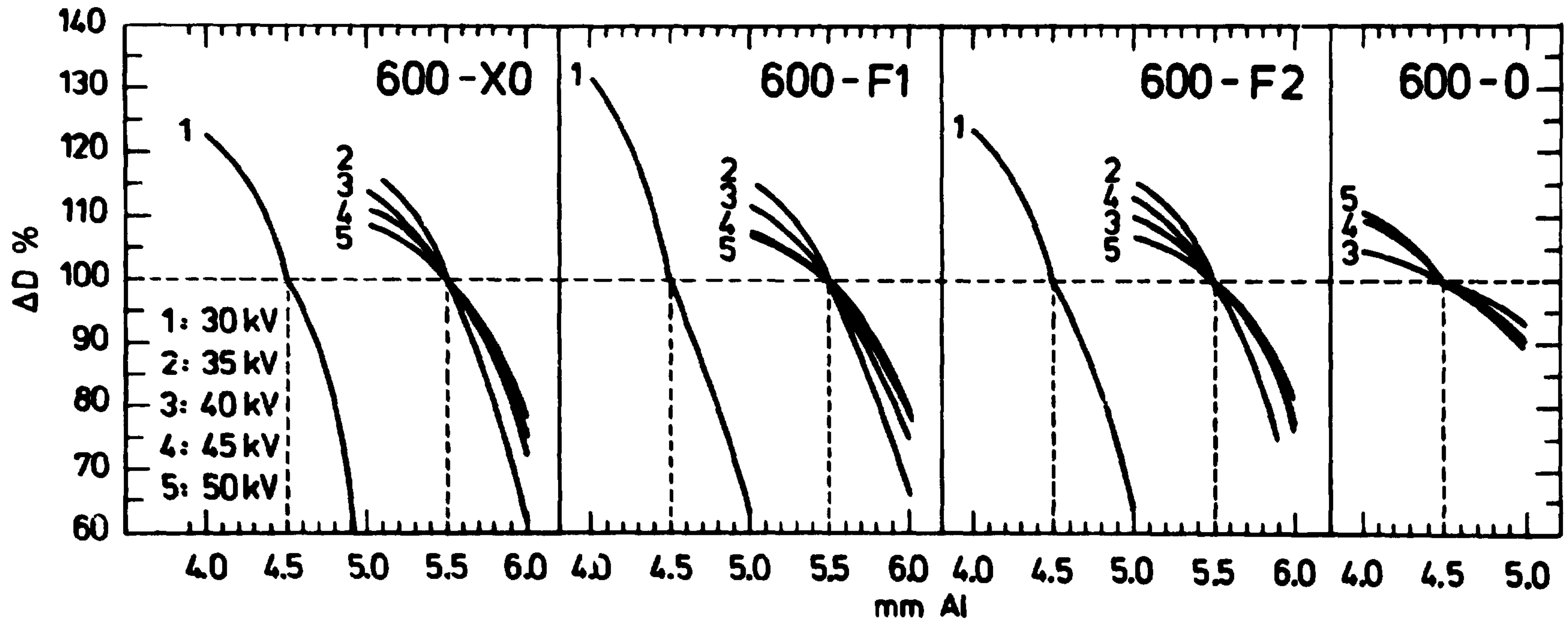

Fig. 53. As fig. 52, for the 600 paper.

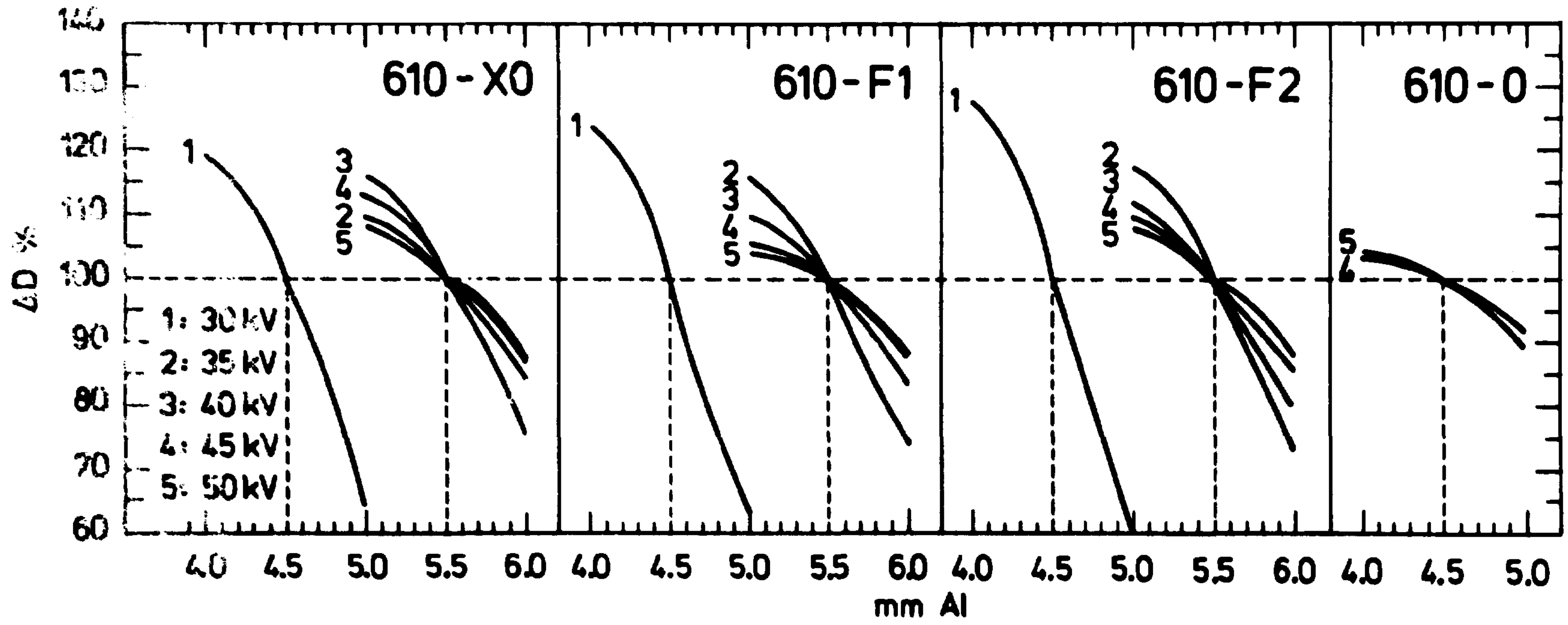

Fig. 54. As fig. 52, for the 610 paper.

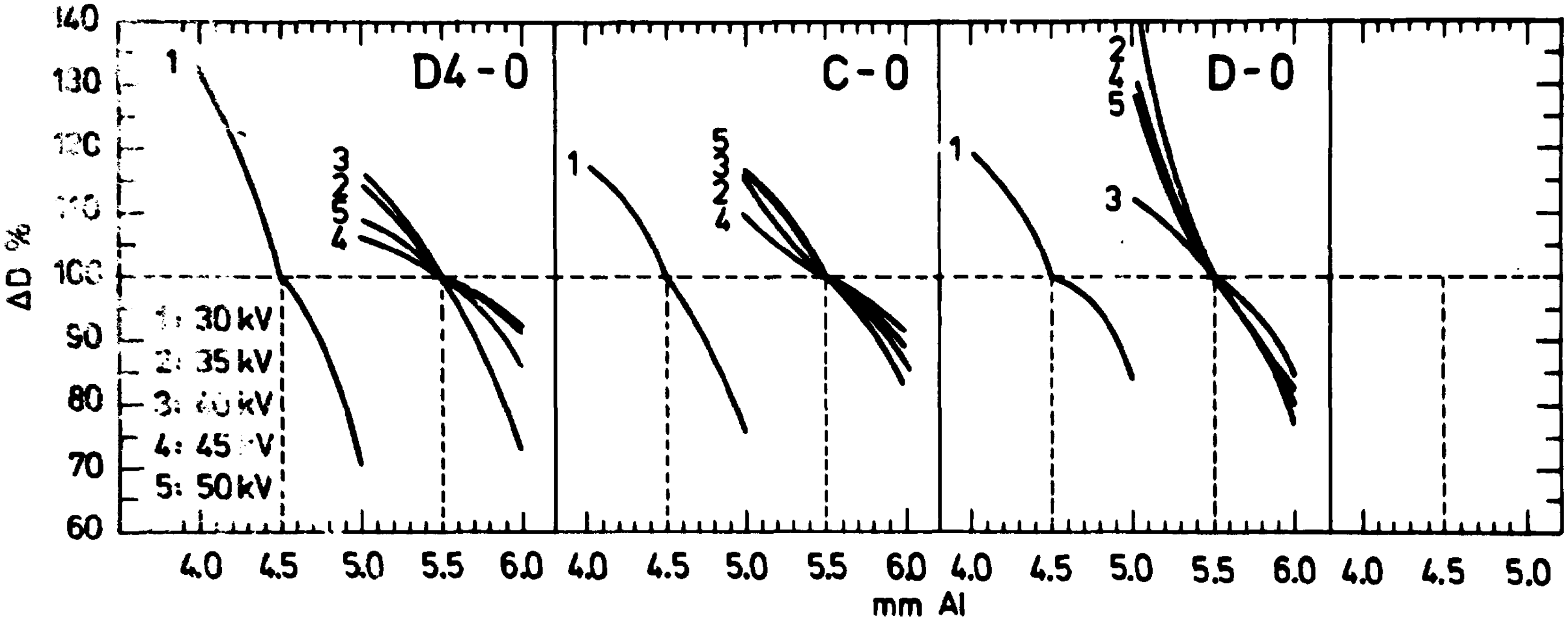

Fig. 55. As fig. 52, the D4, C and D films.

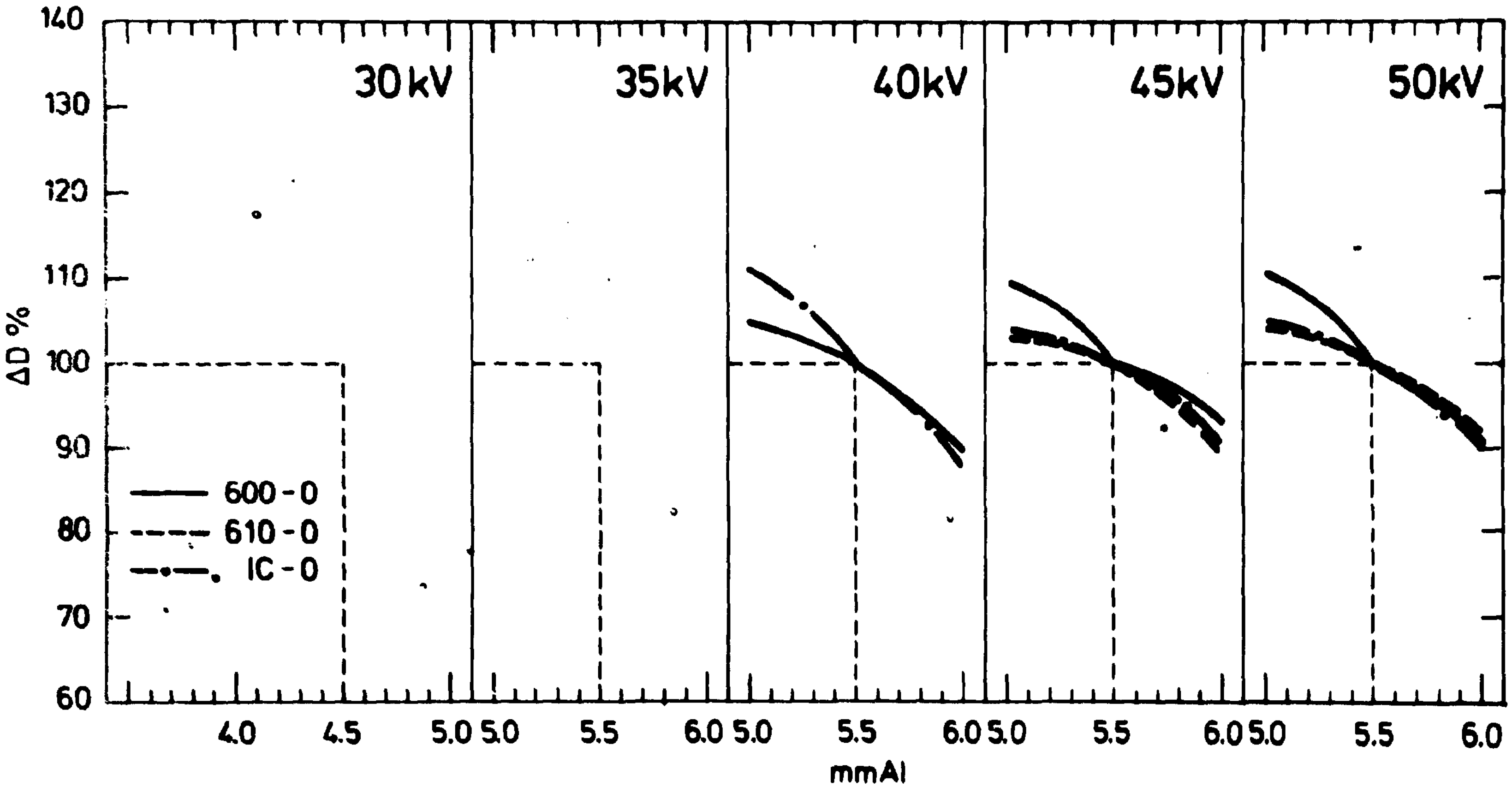

Fig. 56. As fig. 52, for IC, 600 and 610 paper exposed without screen.

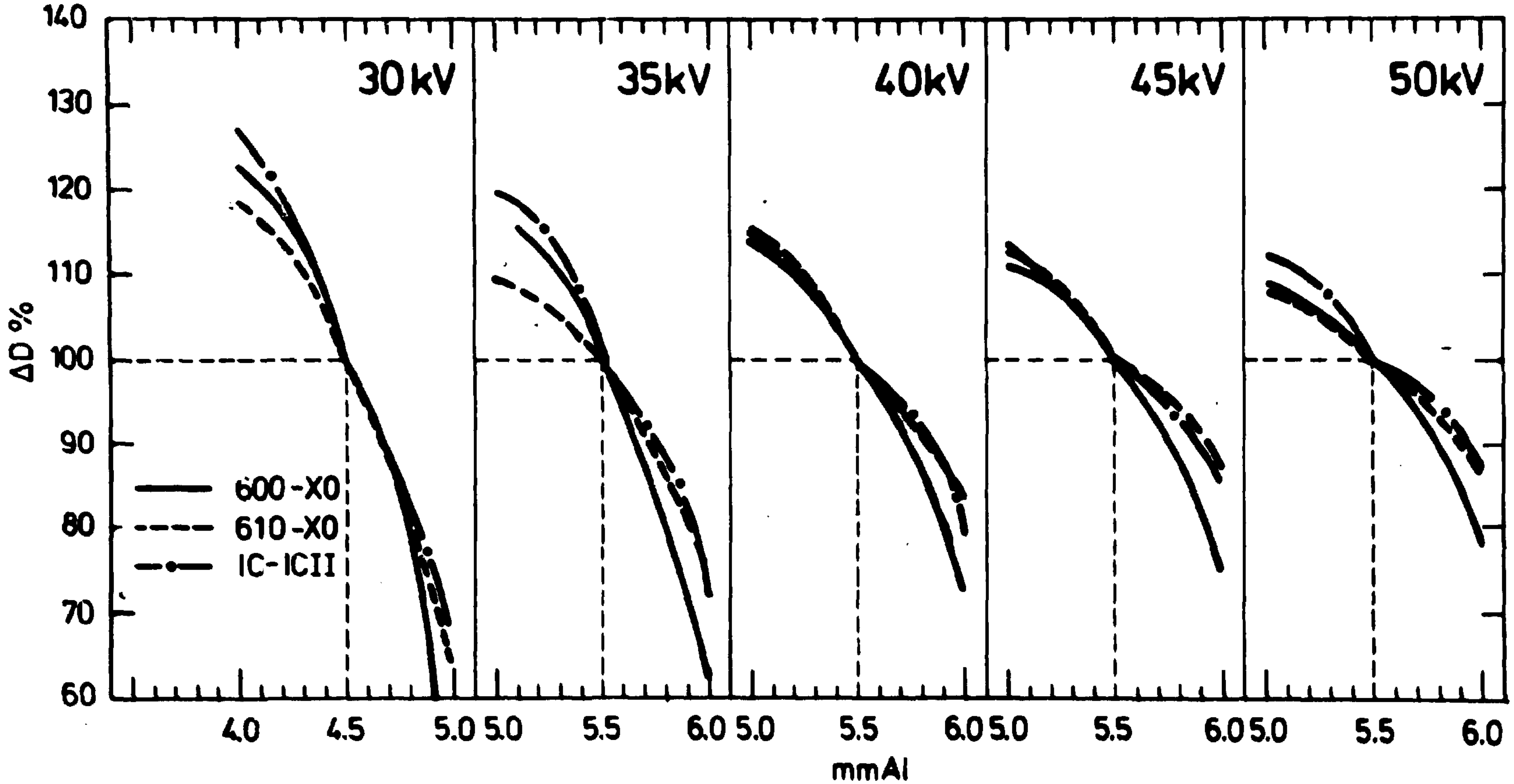

Fig. 57. As fig. 52, for IC, 600 and 610 paper ex posed with screen.

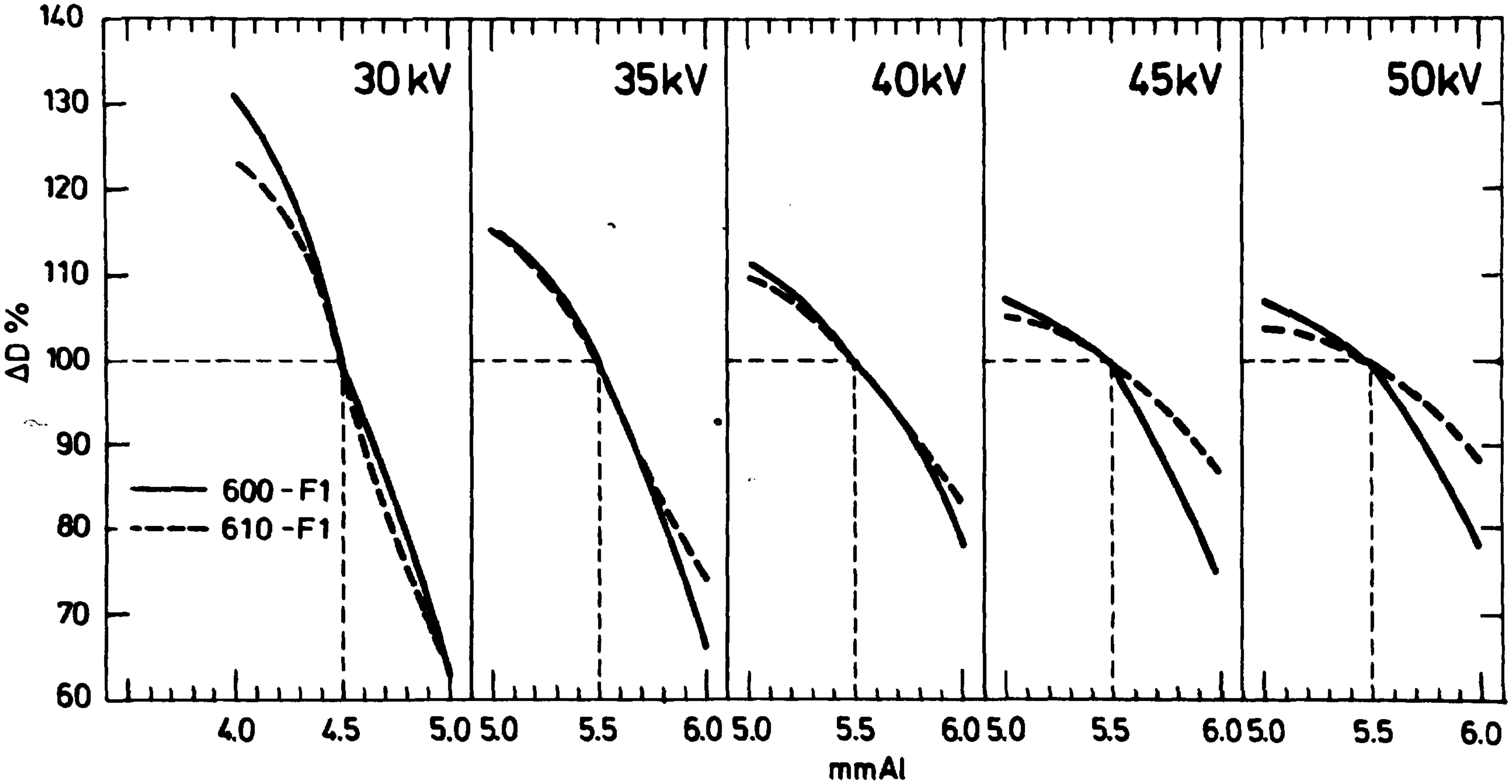

Fig. 58. As fig. 52, for 600 and 610 paper exposed with F1 screen.

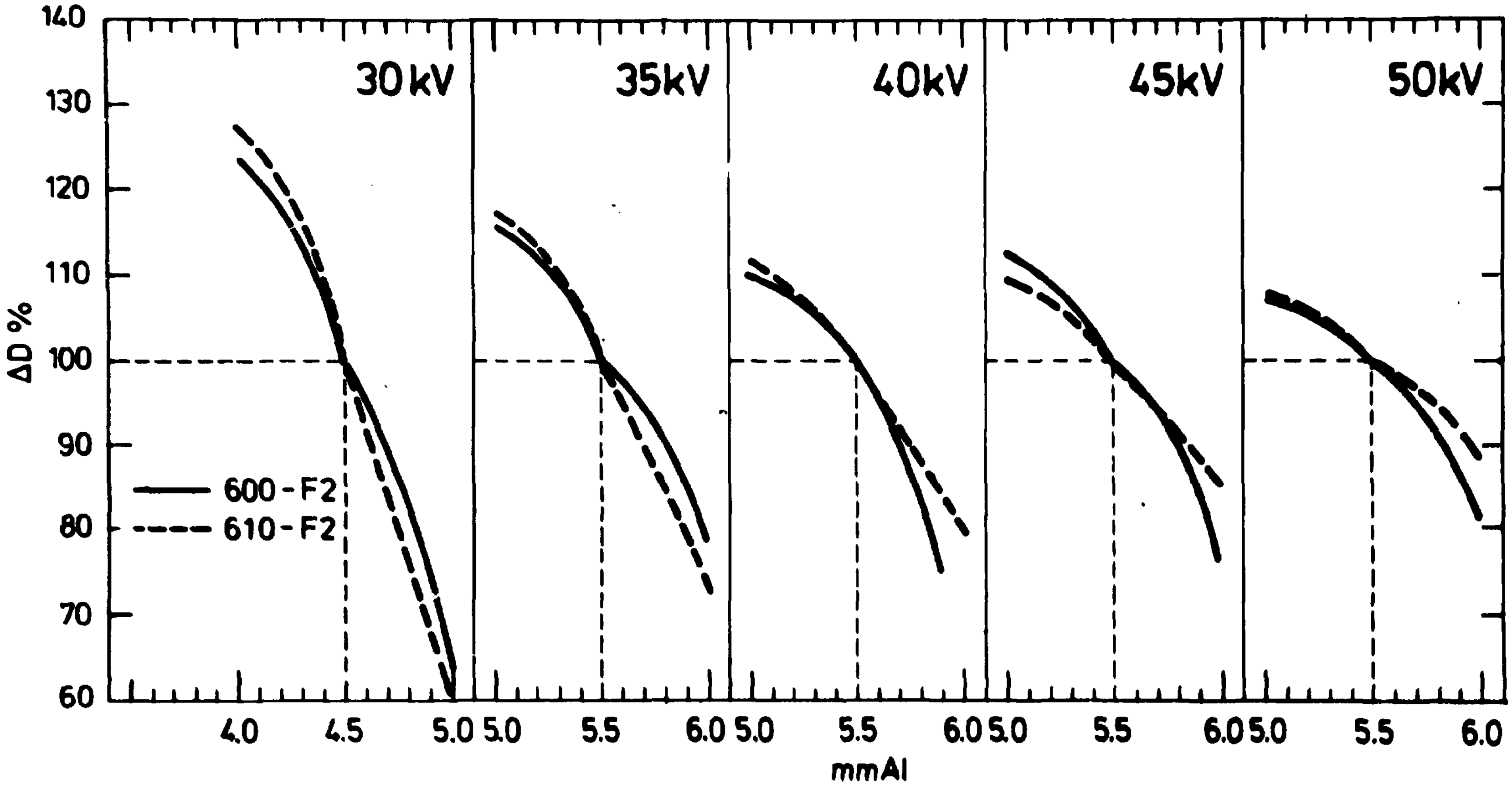

Fig. 59. As fig. 52, for 600 and 610 paper exposed with F2 screen.

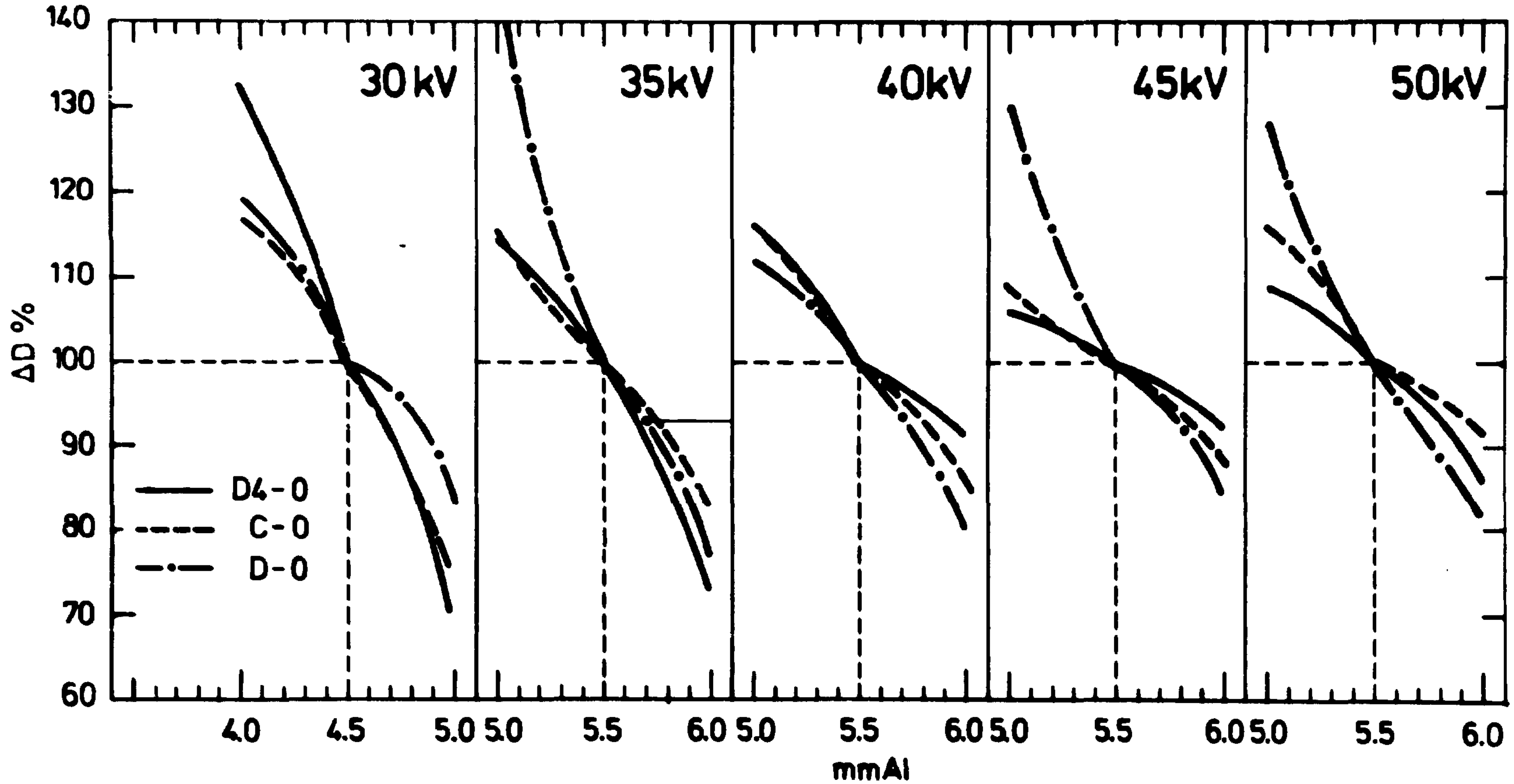

Fig. 60. As fig. 52, for D4, C and D films exposed without screens.

7.2. Radiographic quality of U/Al blocks

To assess the quality of the radiographs of the U/Al blocks from which the U/Al plates were produced (by consecutive rolling down), a sample was taken of a 30 mm block, in which five circular holes were drilled (near the top of the block). The holes had the following diameters: 1.5, 0.9, 0.6, 0.5 and 0.4 mm (which corresponds to 5, 3, 2, 1.67 and 1.33% of the block thickness). A 0.6 mm U/Al plate was placed on the top of the block. Holes with diameters corresponding to 1, 2 and 4 times the plate thickness (0.6, 1.2 and 2.4 mm) were drilled in this plate. The holes drilled into the block could be regarded as equivalent to the ISO-type IQIs, whereas the plate was made according to the ASTM penetrameter.

The test block was thereafter radiographed on Agfa-Gevaert D4 and Kodak C film and on Kodak and Agfa-Gevaert X-ray paper.The radiographs were taken with the Andrex 300 kV X-ray machine at various kilovoltages and 5mA (maximum current) at 1 m FFD. Exposure times were chosen so as to reach an adequate density of the radiographs. For practical reasons, 10 min was chosen as maximum exposure. The investigation started with 300 kV and was carried out to lower kilovoltages until the practical limit of a 10 min exposure was reached.

Exposures on films were taken with 0.05 + 0.1 mm Pb intensifying screens. A 0.05 mm Pb filter was placed on top of the cassettes with the X-ray paper. This improved the quality of the radiographs.

The D4 film could not be used for the comparison of IQI sensitivities, because adequate film densities could not be achieved within the 50 mAmin exposure adopted as maximum. Therefore, the Kodak C X-ray film (faster but with larger grain) was used.

The results of the investigation (carried out between 150 and 300 kV) showed that on all radiographs (paper as well as film) the 2% drilled hole (ISO-type IQI) and the 4T hole (ASTM penetrameter) could be seen. It was impossible to achieve better sensitivities even when using a voltage as low as 120 kV. This means that, although the 0.6 mm hole could be easily seen, the 0.5 mm hole is already invisible. This phenomenon could only be explained by the fact that the U/Al casting forms a dispersed alloy and that the grain size of the uranium present in the dispersed alloy is so large that it prevents the 0.5 mm hole from being seen on the radiographs.

7.3. Radiographic quality of Al and Fe blocks

As mentioned above, the radiographic quality of 10, 20 and 30 mm thick Al and 30 mm Fe plates was assessed by the use of wire IQIs. The results are shown in table 25.

Table 25

Radiographic quality of Al, Fe and U/Al blocks

Block of		Al				Fe	U/Al
Thickness - mm		10	20	30	30	30	30
X-ray machine		50 kV, Be-window, 0.5 mm focus			180 kV, 2.3 mm	300 kV, 3 mm focus	
kV range		35 - 50	45 - 50	50	75 - 180	170 - 300	120 - 300
% IQI sensitivity							
Paper	610-X0,F1	1.25 - 2.0	1.0	0.83	0.83 - 2.1	1.33 - 1.67	2.0
Paper	610-F2	1.25 - 1.6		0.83			
Paper	IC-IC II		0.8 - 1.0	0.83	1.07 - 2.1	1.33 - 2.10	2.0
Film - C		1.0 - 1.35	0.63	0.53	0.67 - 1.33	0.83	2.0

As can be seen, in all cases sensitivities of better than 2% could be reached for paper radiographs. On film radiographs of Al and Fe plates, one to two more wires could be seen, whereas on U/Al blocks a 2% sensitivity was obtained both for paper and film. (For reasons explained in 7.2 above).

7.4. Radiographic quality of fiber reinforced composites

Similar difficulties were encountered during the control of fiber-reinforced composites as with the control of the radiographic quality of U/Al plates. Also here it was impossible to use the standard IQIs and therefore a similar approach was chosen as with the U/Al plates: paper (or film) density contrast was used to assess the quality of the radiographs.

On a specimen (2 mm thick) of a commercial carbon fibre epoxy material (produced by pultrusion), containing about 60% long, parallel fibres, steps were ground down, reducing the original sample thickness by 10, 20, 35 and 50 µm (this corresponds to a 0.5, 1.0, 1.7 and 2.5% thickness reduction).

The sample was next radiographed on radiographic paper and paper densities were read under the different parts of the sample.

Radiography of fibre-reinforced composites with thicknesses of 2 to 3 mm requires very soft X-rays. In the investigation reported in 20) voltages down to 10 kV were used. For such soft X-rays it was impossible to use the standard aluminium rigid cassettes. Therefore vacuum plastic cassettes were used in which the IC II intensifying screen was placed under the radiographic paper (X-ray films were exposed without screen in the same plastic cassettes).

On paper radiographs (exposed at 11 kV) a 2.5% reduction of the sample thickness could be seen for the IC paper whereas on the 600 paper a 1.7% reduction could be seen.

Film radiographs, taken at 10 to 15 kV, showed better density contrast. On several brands of film even the smallest reduction of 10 µm (or 0.5%) could be observed.

8. EXPOSURE CHARTS

In all paper radiography work performed routinely at Risø for the quality control of U/Al blocks and plates for MTR fuel elements and to investigate samples of fiber-reinforcec composites, the thickness of the radiographed object is fixed, and optimum exposure conditions are determined for this particular thickness.

Radiographic paper can, however, be used with advantage in other fields of radiography and especially for the radiographic control of objects made of aluminium or steel. As objects made of these materials may differ in thickness, it is necessary to have adequate exposure charts for such materials in order to avoid the time-consuming "try-and-error" method of finding adequate exposure conditions.

Below are given exposure charts for Al and Fe produced for various combinations of radiographic paper and screen. They are further compared with similar charts for X-ray films.

8.1. Production of the charts

The procedure described below was chosen from several existing methods of exposure chart production.

The Al or Fe step wedges, described in 4.5 above and shown on fig. 23, were exposed at different kilovoltages using different exposures (mAmin) at the same FFD = 1 m. For each kV setting and each exposure (in mAmin), optical densities under all the Al or Fe steps were measured and plotted as function of the step thickness (see fig. 61). Table 26 gives an example of such density readings (from which the curves of fig. 61 were plotted) under different steps of an Al step wedge exposed at 50 kV on Kodak 600 paper with X0 screen at FFD = 1 m (beryllium window tube, Balteau 50 kV X-ray machine).

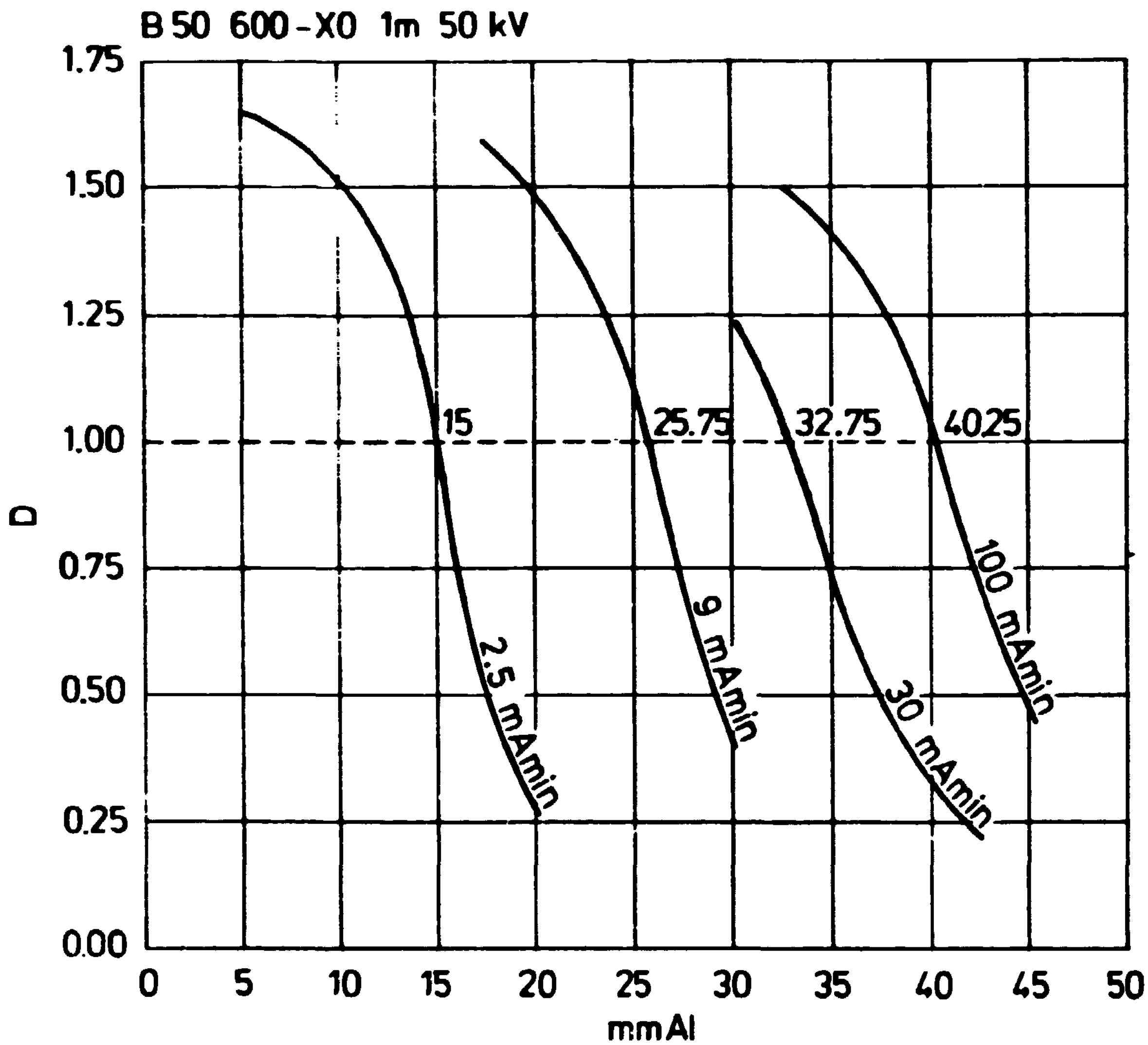

Fig. 61. Paper density under different steps of the Al step wedge exposed at 50 kV.

The exposure charts should be plotted for paper density D_p = 1.0. Therefore intersections of the different thickness-density curves with this density are found from fig. 61 and are tabulated at the bottom of table 26. From these data an exposure chart for 50 kV can be produced, because these readings give the Al thickness under which the density of D_p = 1.0 will be reached at different exposures (in mAmin). The exposure chart is produced in a semilogarithmic scale as shown on fig. 62.

Repeating the procedure described above for other kilovoltages, exposure charts were produced for different paper/screen combinations.

Table 26

Paper densities under different Al steps

Step wedge thickness - mm	Exposure in mAmin			
	2.5	9	30	100
5	1.64			
7.5	1.60			
10	1.53			
12.5	1.34			
15	0.95			
17.5	0.54	1.59		
20	0.28	1.50		
22.5		1.36		
25		1.07		
27.5		0.70		
30		0.40	1.23	
32.5			1.03	1.49
35			0.72	1.42
37.5			0.48	1.29
40			0.29	1.02
42.5			0.21	0.70
45				0.46
mm of Al for D_p = 1.0	15.00	25.75	32.75	40.25

8.2. Exposure charts for aluminium

Using the aluminium step wedges shown on fig. 23 and the technique described in 8.1 above, exposure charts were produced for aluminium up to 35 mm using soft X-rays and up to 70 mm using X-rays in the intermediate voltage range.

In the low voltage range exposure charts were produced using the Baltographe BF 50/20 constant potential X-ray machine with a 0.5 mm focus beryllium window X-ray tube. Voltages from 25 to 50 kV were used (in 5 kV increments). All charts were produced at FFD = 1 m and for a paper density of $D_p = 1.0$.

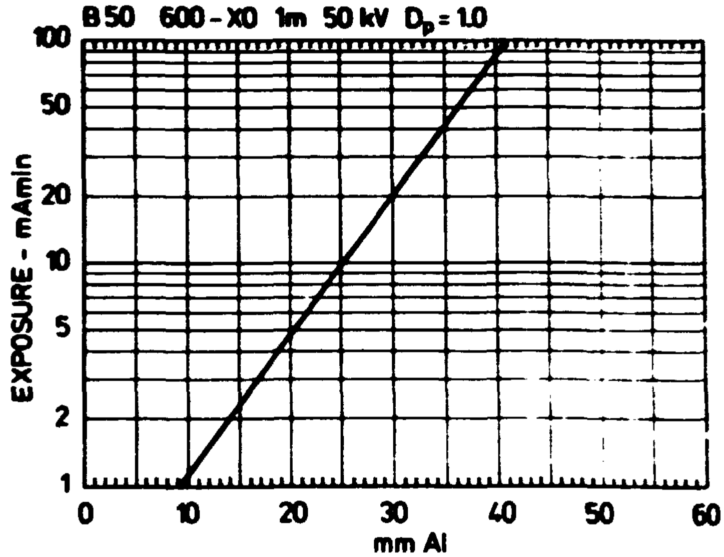

Fig. 62. Exposure chart for Al at 50 kV.

Figure 63 shows an exposure chart for the Agfa-Gevaert Structurix IC paper exposed with an IC II screen. On the following figures similar charts are shown for the Kodak Industrex Instant paper and Kodak intensifying screens. Figures 63 to 65 give the charts for the 600 paper exposed with the X0, F1 and F2 screens, while figs. 67 to 69 give charts for the 610 paper exposed with the same screens. For the sake of comparison an exposure chart is given on fig. 70 for the Agfa-Gevaert Structurix D7 X-ray film as supplied with the Balteau X-ray machine.

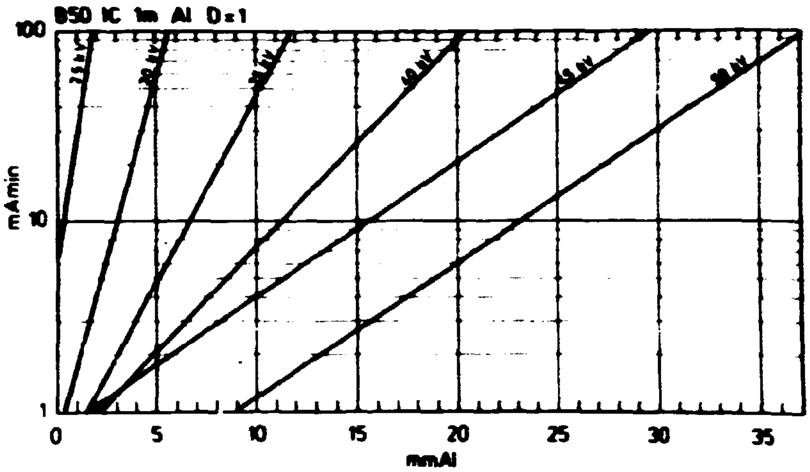

Fig. 63. Exposure charts for Al for Agfa-Gevaert Structurix IC paper exposed with IC II screen.

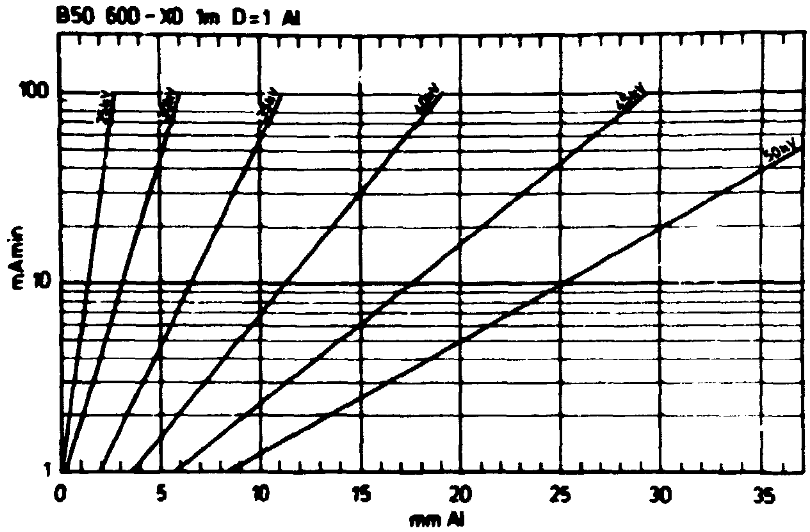

Fig. 64. Exposure charts for Al for Kodak Industrex Instant 600 paper exposed with X0 screen.

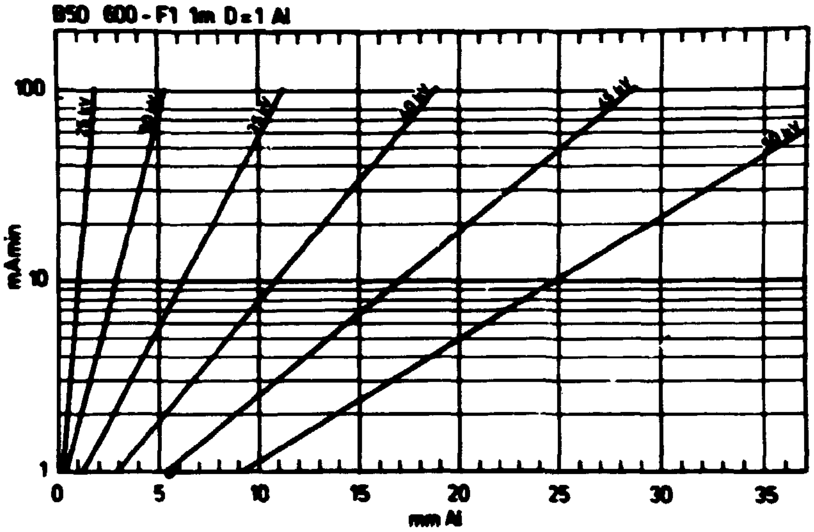

Fig. 65. As fig. 64, for the 600 - F1.

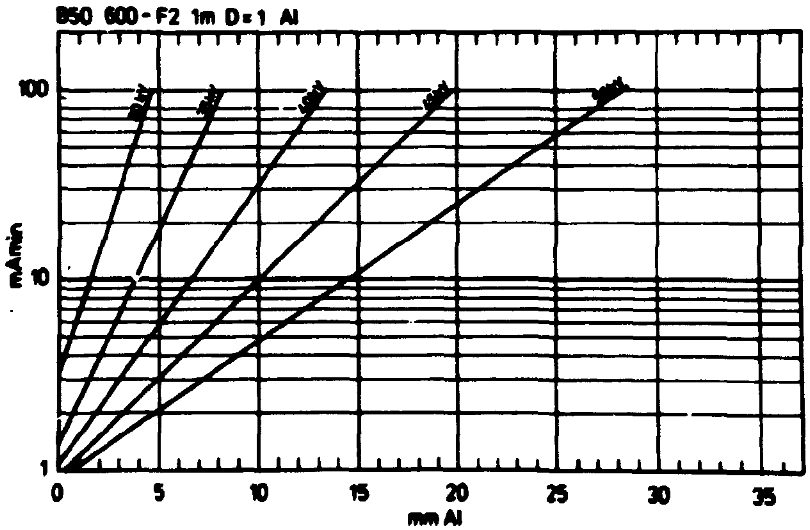

Fig. 66. As fig. 64, for the 600 - F2.

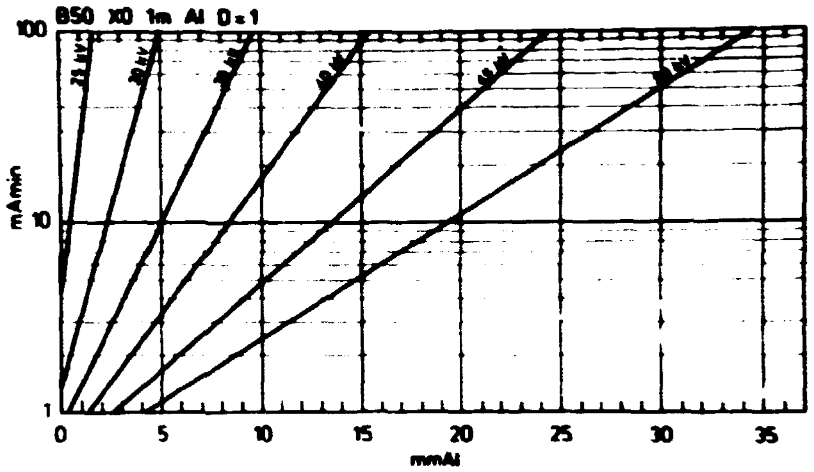

Fig. 67. As fig. 64, for the 610 - X0.

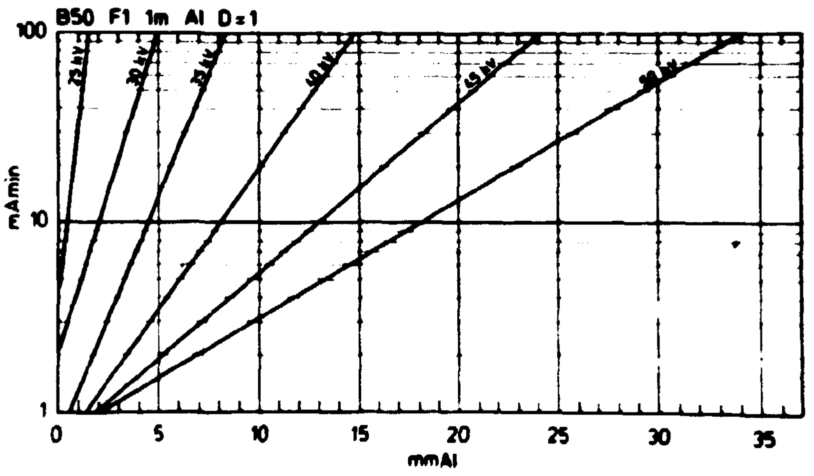

Fig. 68. As fig. 64, for the 610 - F1.

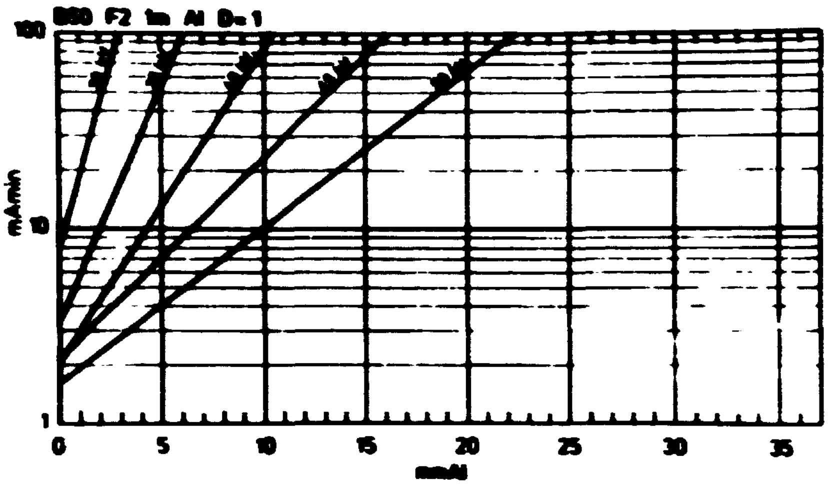

Fig. 69. As fig. 64, for the 610 - F2.

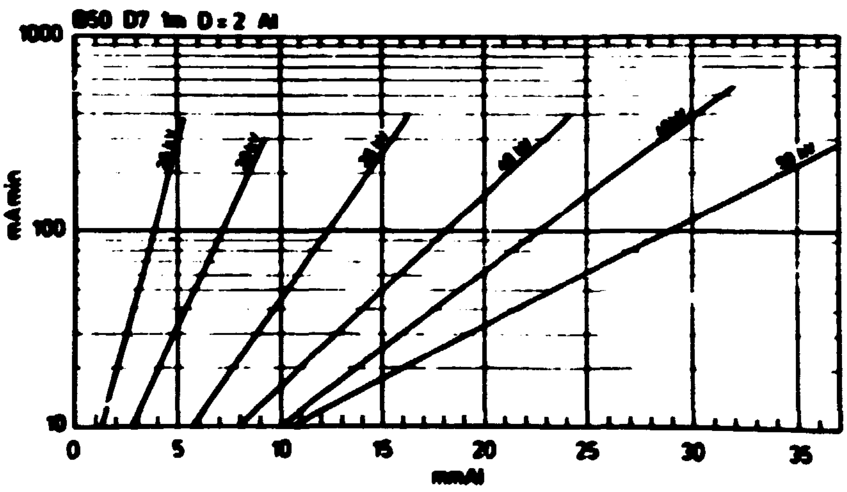

Fig. 70. Exposure chart for Al for the Agfa-Gevaert Structurix D7 film. D_f = 2.0 (Balteau).

In the intermediate voltage range the Andrex 180 kV X-ray machine (self-contained, with a 2.3 mm focus X-ray tube) was used to produce exposure charts for aluminium. FFD = 1 m and D_p = 1.0. Voltages from 50 to 130 kV were used (with 20 kV increment). A 0.05 mm lead filter was used on the cassette.

Figure 71 shows the exposure chart for the IC paper with the IC II screen. Figures 72 to 77 show similar charts for the Kodak papers and screens.

To be able to compare exposure charts for paper with those for the X-ray film on figs. 78 and 79, exposure charts are reproduced for the D4 and D7 films (after Agfa-Gevaert pamphlet[24]). The films were exposed without intensifying screens and the charts were recalculated for the FFD = 1 m.

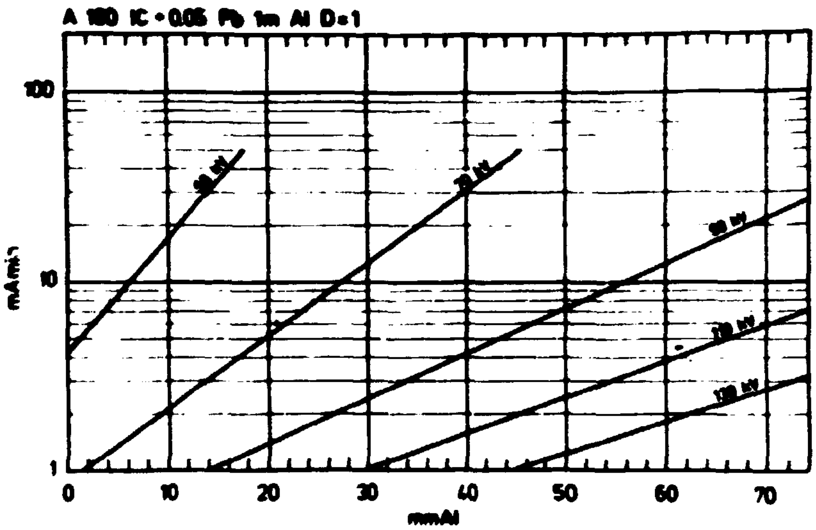

Fig. 71. Exposure chart for Al for the IC paper with IC II screen.

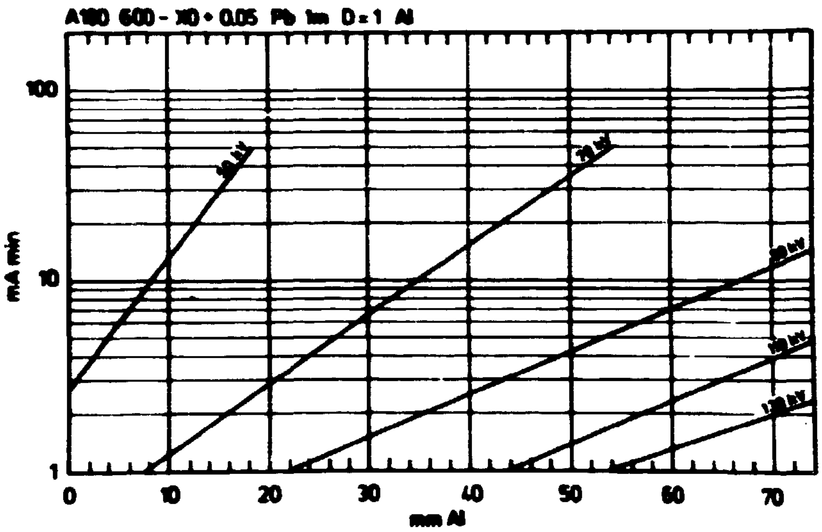

Fig. 72. As fig. 71, for the 600 - X0.

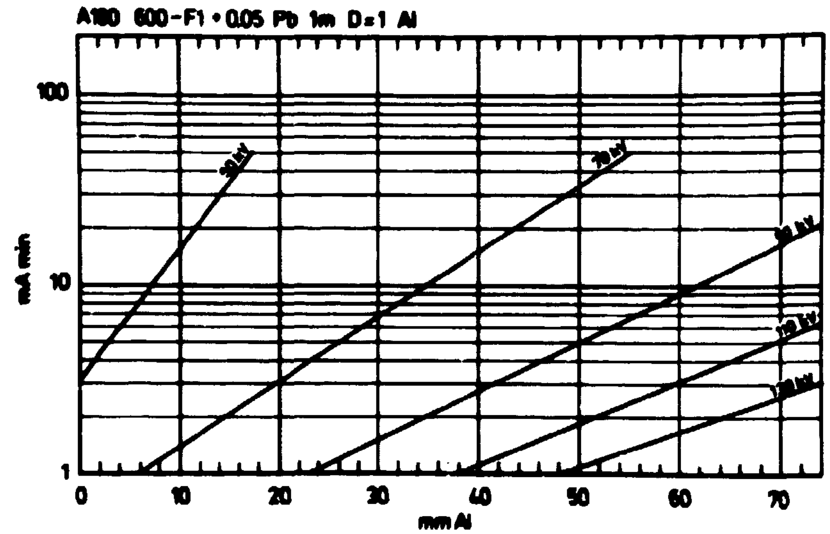

Fig. 73. As fig. 71, for the 600 - F1.

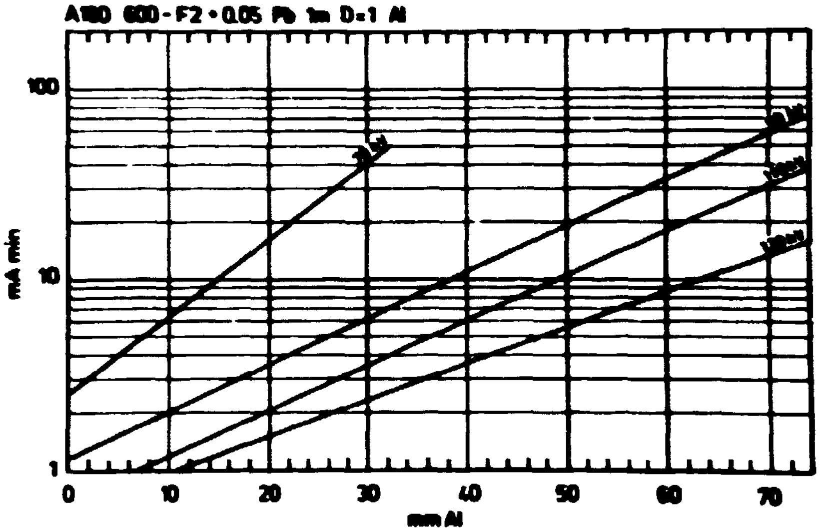

Fig. 74. As fig. 71, for the 600 - F2.

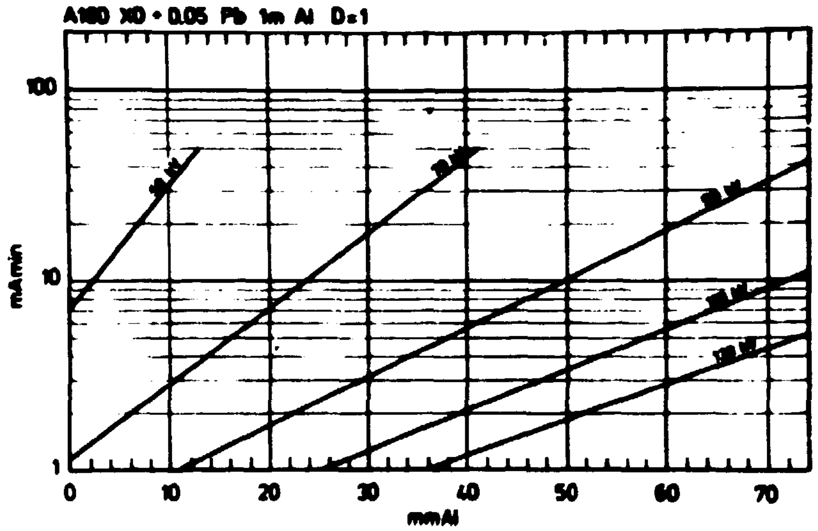

Fig. 75. As fig. 71, for the 610 - X0.

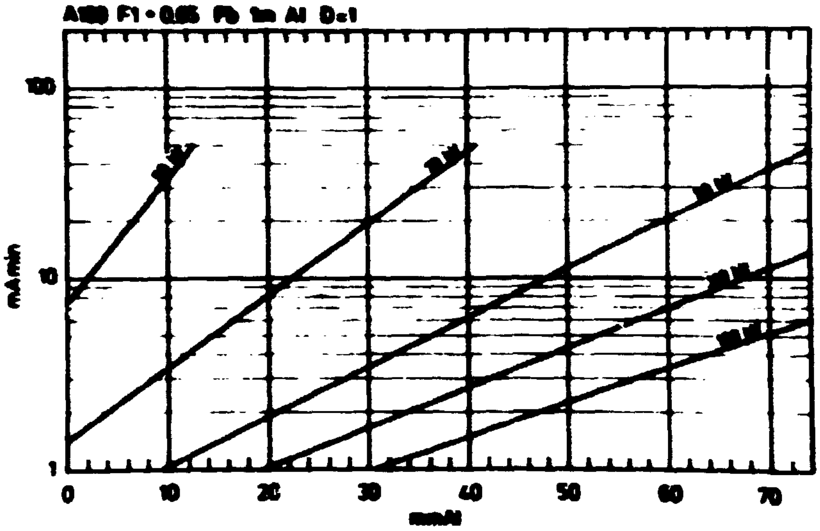

Fig. 76. As fig. 71, for the 610 - F1.

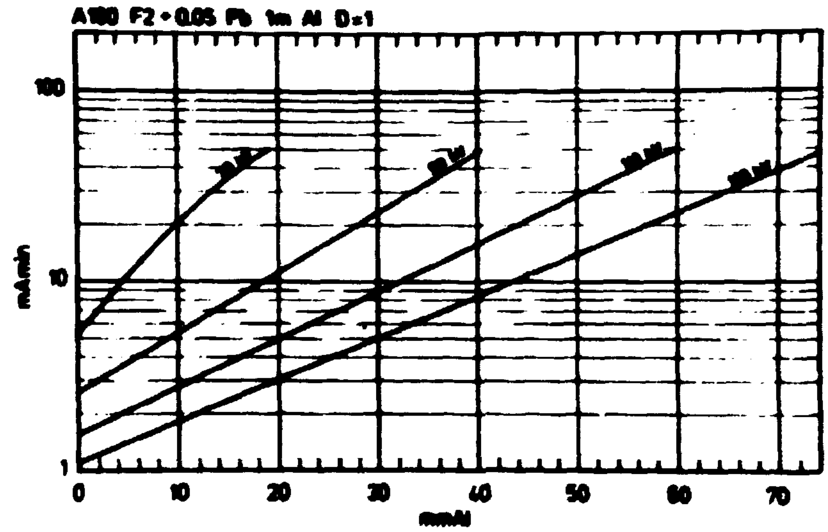

Fig. 77. As fig. 71, for the 610 - F2.

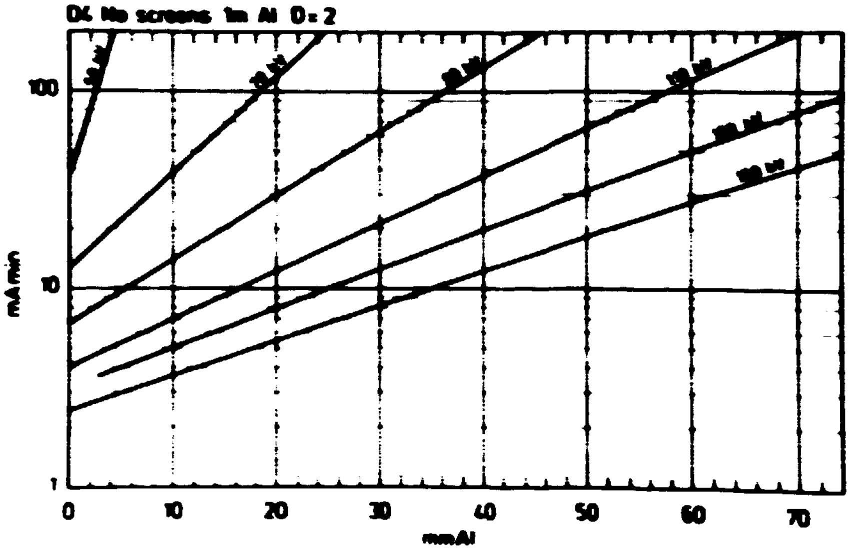

Fig. 78. Exposure chart for Al for the D4 film exposed without intensifying screens.

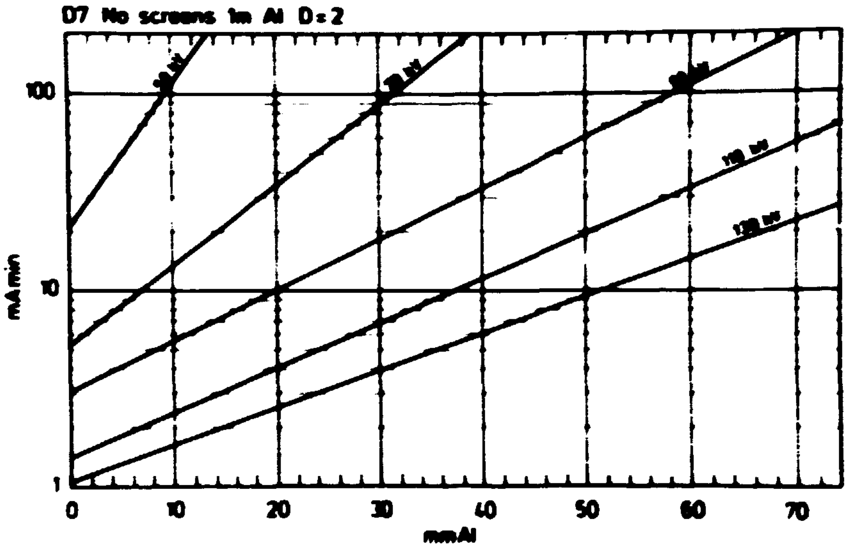

Fig. 79. As fig. 78, for the D7 film.

8.3. Exposure charts for steel

Using the steel step wedge shown on fig. 23 and the technique described in 8.1 above, exposure charts were produced for steel up to 70 mm using the Andrex 300 kV X-ray machine (self-contained, with a 3.0 mm focus X-ray tube). Voltages from 100 to 300 kV (in 20 kV increments) were used. A 0.05 mm lead filter was placed on the cassette. The charts were produced at FFD = 1 m for D_p = 1.0.

Figure 80 gives the exposure chart for the IC paper and the IC II screen, while figs. 81 to 84 give similar charts for the 600 and 610 papers with X0 and P1 screens.

The following figures give exposure charts for Agfa-Gevaert D4, D7 and D10 and Kodak M, C, D and Kodirex films. The exposure curves are reproduced after the Andrex exposure calculator. On figs. 85 to 87 additional curves are given after [24]. The Andrex calculator does not specify the thickness of the lead intensifying screens, whereas the Agfa-Gevaert pamphlet[24] uses 20 µm Pb screens. The exposure charts shown on figs. 85 to 91 were computed for FFD = 1 m and D_f = 2.0

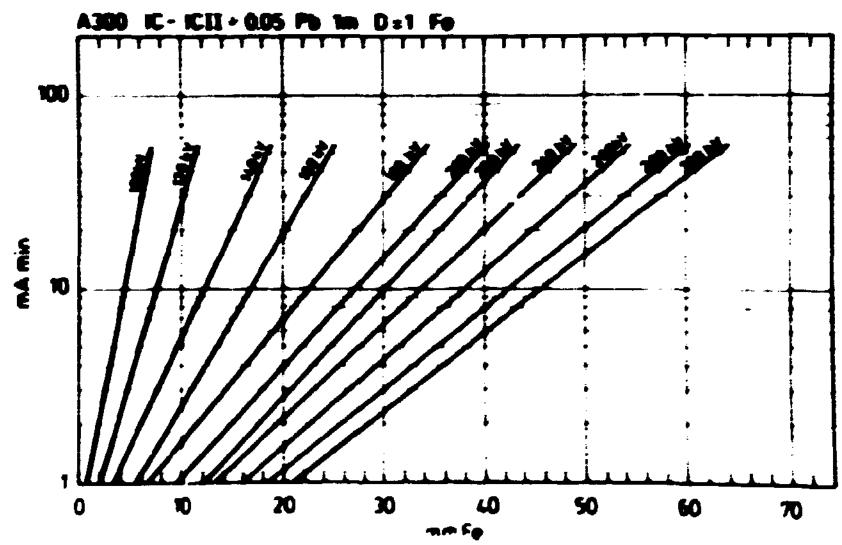

Fig. 80. Exposure chart for Fe for the IC paper with IC II screen.

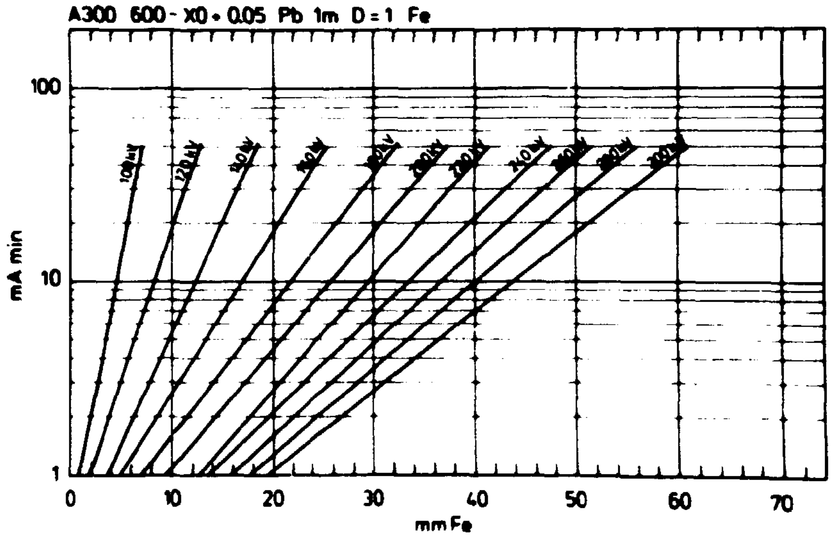

Fig. 81. As fig. 80, for the 600 - X0.

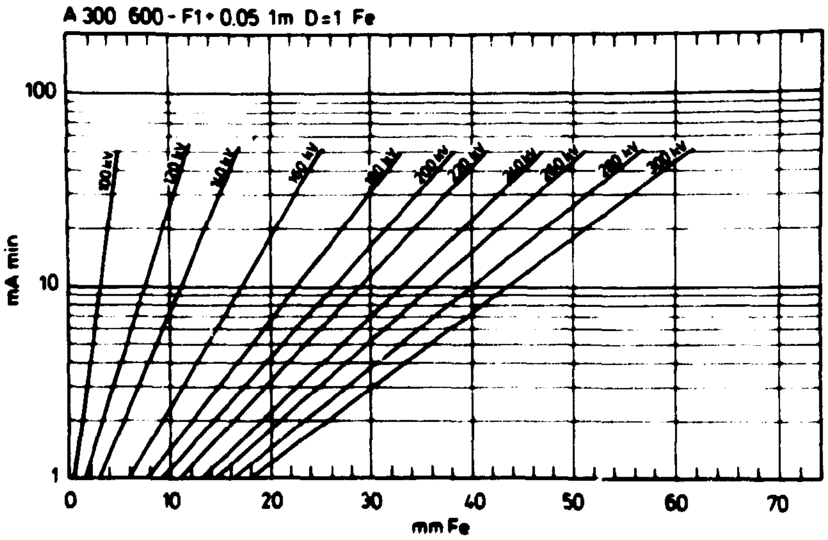

Fig. 82. As fig. 80, for the 600 - F1.

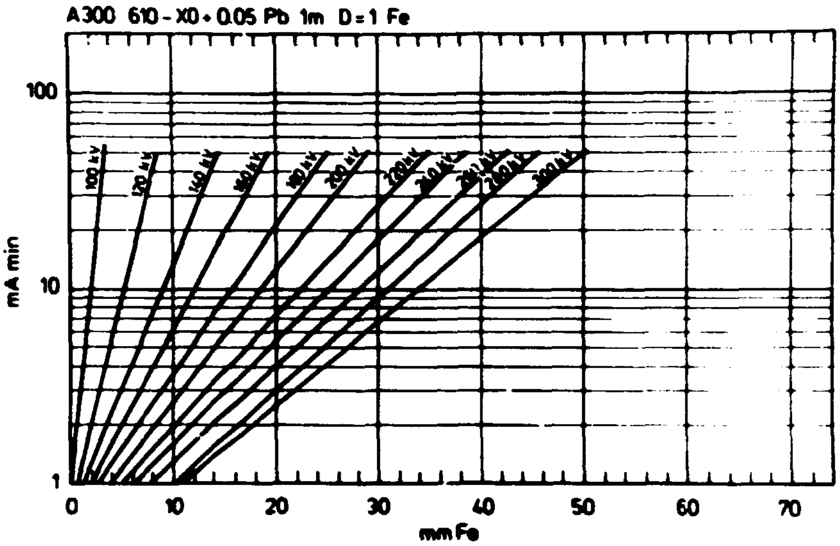

Fig. 83. As fig. 80, for the 610 - X0.

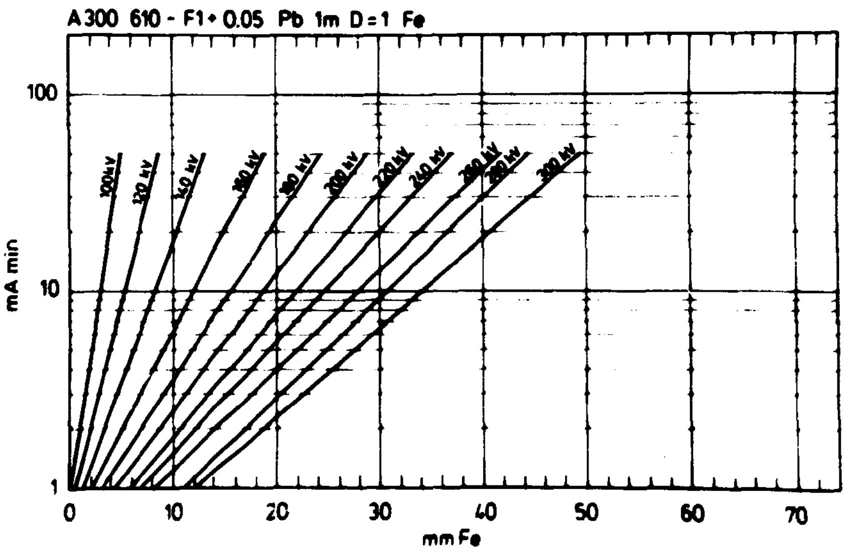

Fig. 84. As fig. 80, for the 610 - F1.

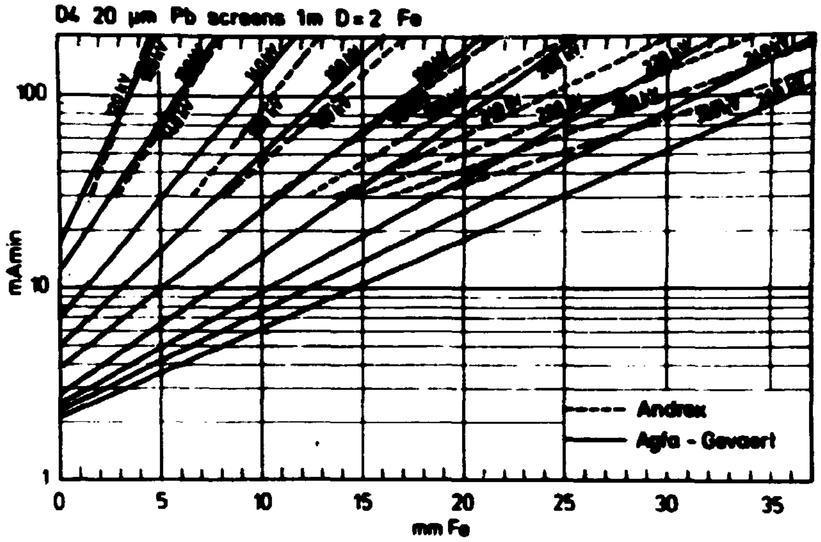

Fig. 85. Exposure chart for Fe for the Agfa-Gevaert Structurix D4 film.

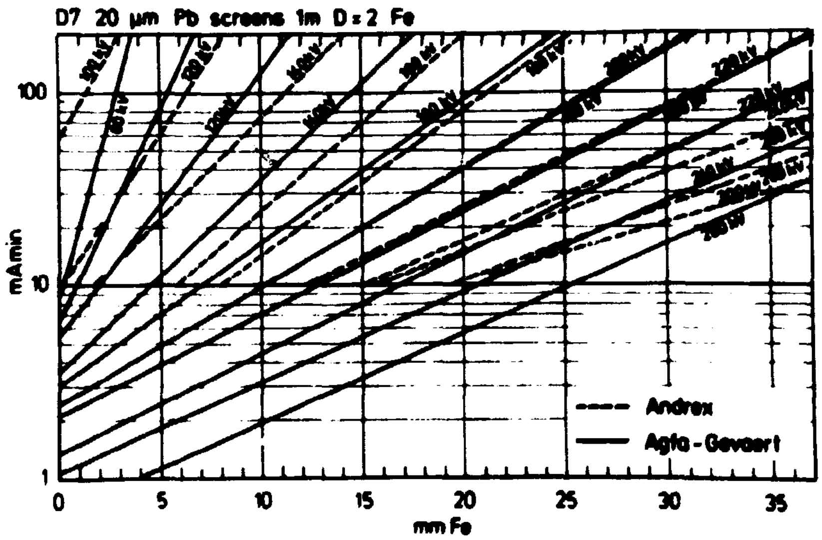

Fig. 86. As fig. 85, for the D7 film.

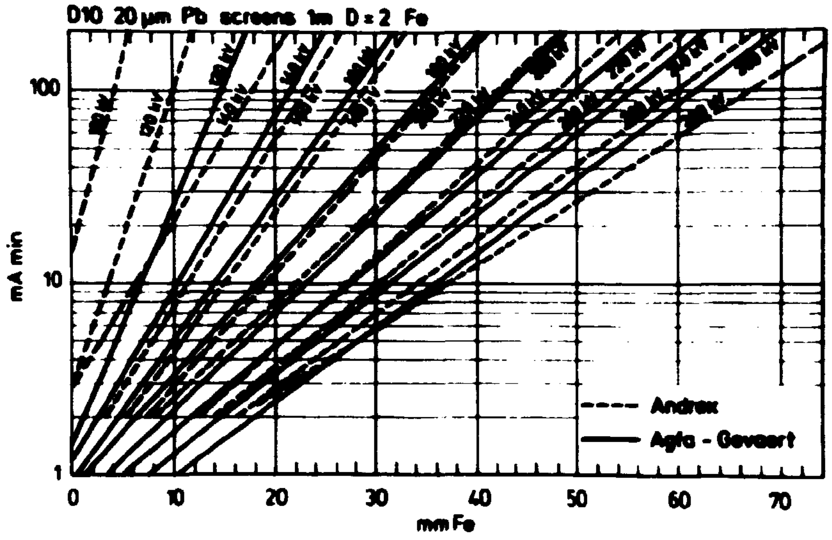

Fig. 87. As fig. 85, for the D10 film.

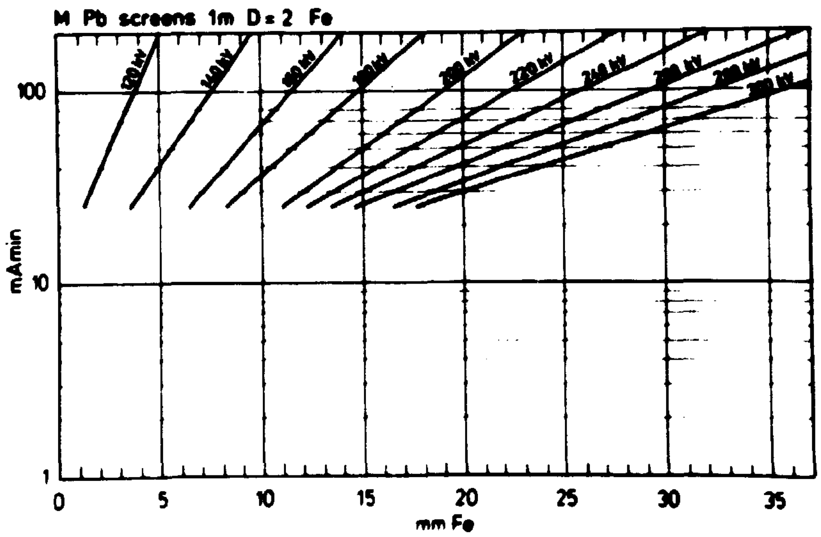

Fig. 88. Exposure chart for Fe for the Kodak Industrex M film.

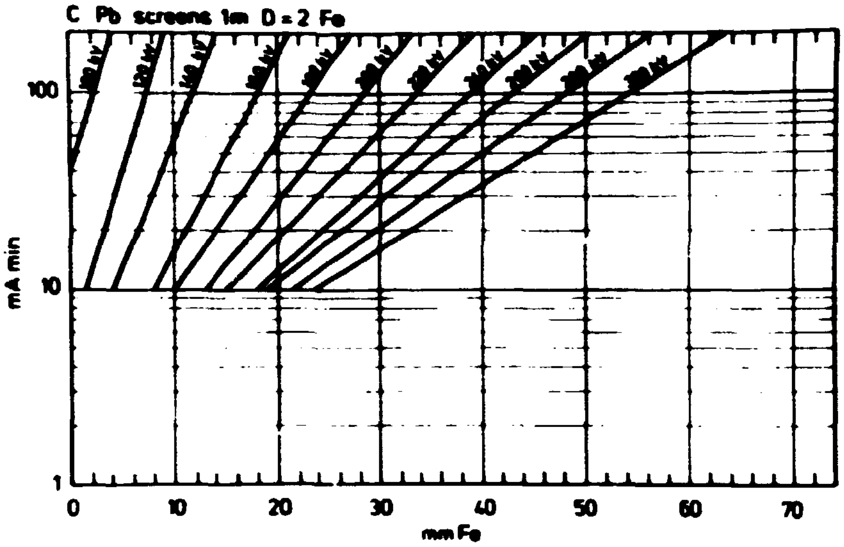

Fig. 89. As fig. 88, for the C film.

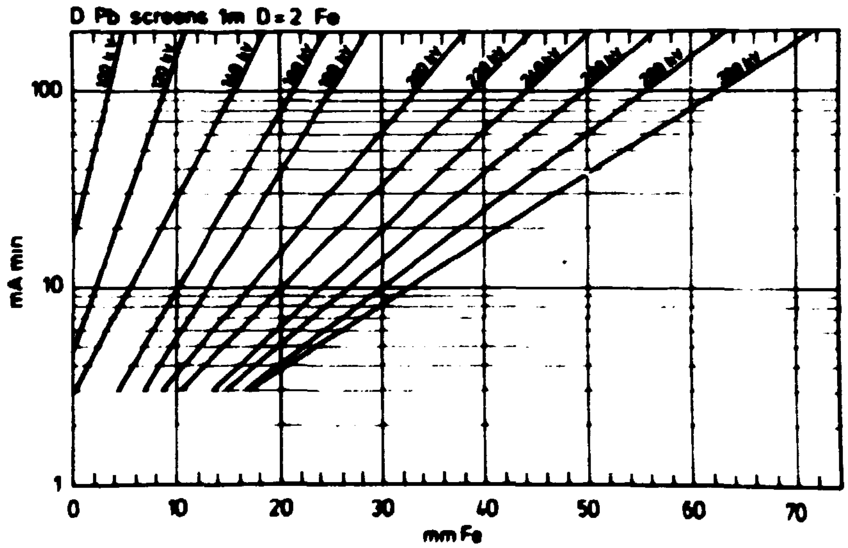

Fig. 90. As fig. 88, for the D film.

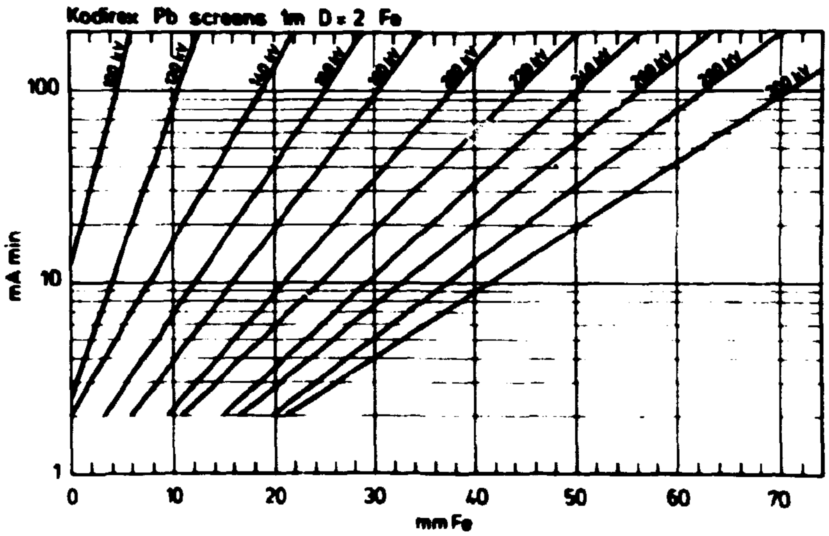

Fig. 91. As fig. 88 for the Kodirex film.

8.4. Relative speed

In chapter 6.1 the relative speed of different radiographic paper and screen combinations was calculated from the characteristic curves of the paper. The relative speed can, however, also be calculated from the exposure charts. Relative speed calculations performed from the characteristic curves were made only for one value of filtration used for the production of a particular charteristic curve. Relative speed calculations from exposure charts can be made for different values of filtration.

In table 27 the relative speed values calculated from exposure charts for aluminium in the low voltage range are given. Table 28 gives similar values for Al in the intermediate voltage range, while table 29 gives the relative speed calculated from exposure tables for steel.

The relative speed was calculated by comparing the exposures (in mAmin) necessary to obtain the same densities for the same thickness of the radiographed material. Next the exposure for the slowest paper-screen combination or film was used as reference, giving the relative speed of 1.0. All other paper-creen combinations required lower exposures and therefore show a higher relative speed.

Table 27 . Relative speed (from exposure charts for Al) in the low voltage range.

X-ray machine	Paper Film	Screen	mm Al	kV 30	35	40	45	50
B 50	IC	IC II	1.5	10.4	7.5	-	-	-
			10.0	-	-	11.2	5.8	-
			20.0	-	-	-	-	10.7
	600	XO	1.5	10.4	9.4	-	-	-
			10.0	-	-	12.2	10.0	-
			20.0	-	-	-	-	10.2
		F1	1.5	10.4	6.5	-	-	-
			10.0	-	-	10.5	9.0	-
			20.0	-	-	-	-	12.8
		F2	1.5	2.9	2.5	-	-	-
			10.0	-	-	2.7	2.3	-
			20.0	-	-	-	-	2.6
	610	XO	1.5	5.8	4.2	-	-	-
			10.0	-	-	5.9	4.8	-
			20.0	-	-	-	-	5.3
		F1	1.5	4.3	4.2	-	-	-
			10.0	-	-	4.4	4.2	-
			20.0	-	-	-	-	4.0
		F2	1.5	1.0	1.0	-	-	-
			10.0	-	-	1.0	1.0	-
			20.0	-	-	-	-	1.0
	D7	0	1.5	5.3	3.2	-	-	-
			10.0	-	-	5.2	8.3	-
			20.0	-	-	-	-	1.9

Table 28 . Relative speed (from exposure charts for Al) in the intermediate voltage range.

X-ray machine	Paper Film	Screen	mm Al	kV 50	70	90	110	130
A 180	IC	IC II	10	-	18.6	-	-	-
			30	-	-	25.4	-	-
			60	-	-	-	28.9	27.8
	600	X0	10	-	32.5	-	-	-
			30	-	-	40.7	-	-
			60	-	-	-	47.8	38.5
		F1	10	-	27.9	-	-	-
			30	-	-	40.7	-	-
			60	-	-	-	35.5	29.4
		F2	10	-	6.2	-	-	-
			30	-	-	9.7	-	-
			60	-	-	-	6.1	5.8
	610	X0	10	-	13.9	-	-	-
			30	-	-	19.7	-	-
			60	-	-	-	19.6	17.2
		F1	10	-	11.5	-	-	-
			30	-	-	17.7	-	-
			60	-	-	-	15.7	14.7
		F2	10	-	2.0	-	-	-
			30	-	-	2.7	-	-
			60	-	-	-	2.2	2.2
	D4	0	10	-	1.0	-	-	-
			30	-	-	1.0	-	-
			60	-	-	-	1.0	1.0
	D7	0	10	-	2.9	-	-	-
			30	-	-	3.4	-	-
			60	-	-	-	3.3	3.4

Table 29. Relative speed (from exposure charts for Fe)(A300 X-ray machine).

Paper Film	Screen	mm Fe	kV 100	120	140	160	180	200	220	240	260	280	300
IC	IC II	5	160	65.7	40.0	-	-	-	-	-	-	-	-
		15	-	-	-	45.7	38.2	32.0	31.0	29.2	-	-	-
		40	-	-	-	-	-	-	-	-	28.0	30.0	28.8
600	XO	5	178	63.9	42.8	-	-	-	-	-	-	-	-
		15	-	-	-	47.1	36.1	29.1	32.1	29.2	-	-	-
		40	-	-	-	-	-	-	-	-	24.6	24.0	24.3
	F1	5	53.3	63.0	35.4	-	-	-	-	-	-	-	-
		15	-	-	-	49.2	41.9	29.1	26.5	28.0	-	-	-
		40	-	-	-	-	-	-	-	-	23.3	24.0	23.0
610	XO	5	7.5	25.6	20.7	-	-	-	-	-	-	-	-
		15	-	-	-	16.8	15.1	11.2	11.8	12.1	-	-	-
		40	-	-	-	-	-	-	-	-	9.5	8.9	9.2
	F1	5	48.0	27.1	18.2	-	-	-	-	-	-	-	-
		15	-	-	-	16.0	14.4	11.6	12.2	12.1	-	-	-
		40	-	-	-	-	-	-	-	-	8.5	8.1	9.2
D4	Pb	5	1.0	1.0	1.0	-	-	-	-	-	-	-	-
		15	-	-	-	1.0	1.0	1.0	1.0	1.0	-	-	-
		40	-	-	-	-	-	-	-	-	1.0	1.0	1.0
M	Pb	5	1.25	1.25	1.25	-	-	-	-	-	-	-	-
		15	-	-	-	1.25	1.25	1.25	1.25	1.25	-	-	-
		40	-	-	-	-	-	-	-	-	1.25	1.25	1.25
D7	Pb	5	3.9	3.9	3.9	-	-	-	-	-	-	-	-
		15	-	-	-	3.9	3.9	3.9	3.9	3.9	-	-	-
		40	-	-	-	-	-	-	-	-	3.9	3.9	3.9
C	Pb	5	5.0	5.0	5.0	-	-	-	-	-	-	-	-
		15	-	-	-	5.0	5.0	5.0	5.0	5.0	-	-	-
		40	-	-	-	-	-	-	-	-	5.0	5.0	5.0
D	Pb	5	10.0	10.0	10.0	-	-	-	-	-	-	-	-
		15	-	-	-	10.0	10.0	10.0	10.0	10.0	-	-	-
		40	-	-	-	-	-	-	-	-	10.0	10.0	10.0
D10	Pb	5	15.0	15.0	15.0	-	-	-	-	-	-	-	-
		15	-	-	-	15.0	15.0	15.0	15.0	15.0	-	-	-
		40	-	-	-	-	-	-	-	-	15.0	15.0	15.0
Kodirex		5	20.0	20.0	20.0	-	-	-	-	-	-	-	-
		15	-	-	-	20.0	20.0	20.0	20.0	20.0	-	-	-
		40	-	-	-	-	-	-	-	-	20.0	20.0	20.0

9. SHARPNESS OF THE RADIOGRAPHIC IMAGE

The sharpness of the radiographic image depends on many factors such as radiation source, focus size, focus-film and object-film distance, and grain size of the photographic emulsion. If intensifying screens are used, the sharpness also depends on the grain size of the intensifying material and a good contact between the intensifying screen and the X-ray film or paper. Even with a correctly chosen exposure geometry (giving satisfactory geometric unsharpness), for the same film (or paper) screen combination, one can get radiographic pictures of varying sharpness because of poor contact between screen and film or paper. Therefore this last factor was the subject of a special investigation.

Rigid metal cassettes, up to 50 x 60 cm in size, are used in the control of U/Al fuel plates. For such large cassettes it is rather difficult to obtain good contact between the paper and the intensifying screen. The results of the investigation confirmed this point.

Two types of rigid cassette were tested, one made by Kodak (30 x 40 cm) and the other by Cawo (distributed by Agfa-Gevaert) (18 x 24, 30 x 40, 50 x 60 cm). X-ray pictures were taken of a steel grid to test the contact between paper and screen. If the contact was good, the picture of the grid showed an even distribution of white background (steel grid) and black spots (holes in the grid) but if the contact was poor areas of gray or black appeared on the radiographs. These darker areas indicated that the contact between the fluorescent screen and the radiographic paper was poor and that the light emitted by the screen crystals was spread around the area of poor contact.

First, an X-ray picture of the steel grid was taken using the rigid cassette without intensifying screens (see fig. 92).

Next, different cassettes with intensifying screens were tested in the same way. The tests performed on Kodak rigid cassettes (which have a more robust construction that the Cawo cassettes) showed that the good contact found when using a new cassette (see fig. 93) deteriorates during the use of the cassette. Figure 94 shows a picture taken using a 30 x 40 cm Kodak cassette that had been used for many X-ray exposures. As can be seen, the contact between paper and screen is poor in the

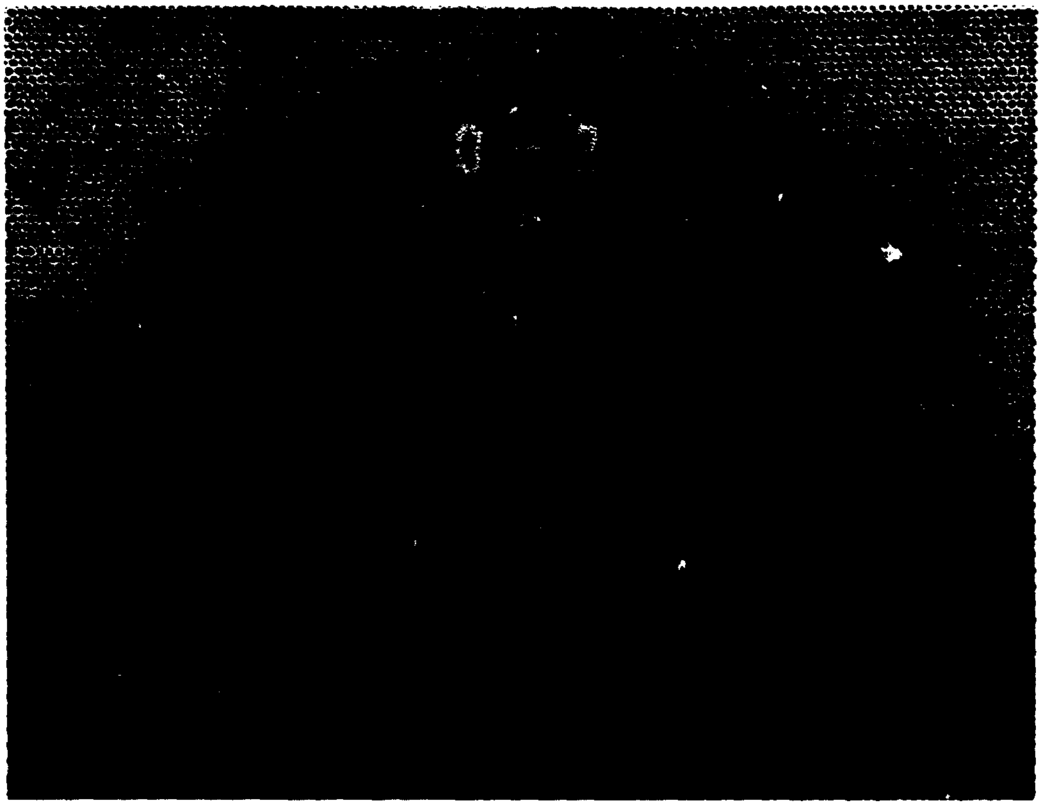

Fig. 92. X-ray picture of a steel grid. Cassette without intensifying screens.

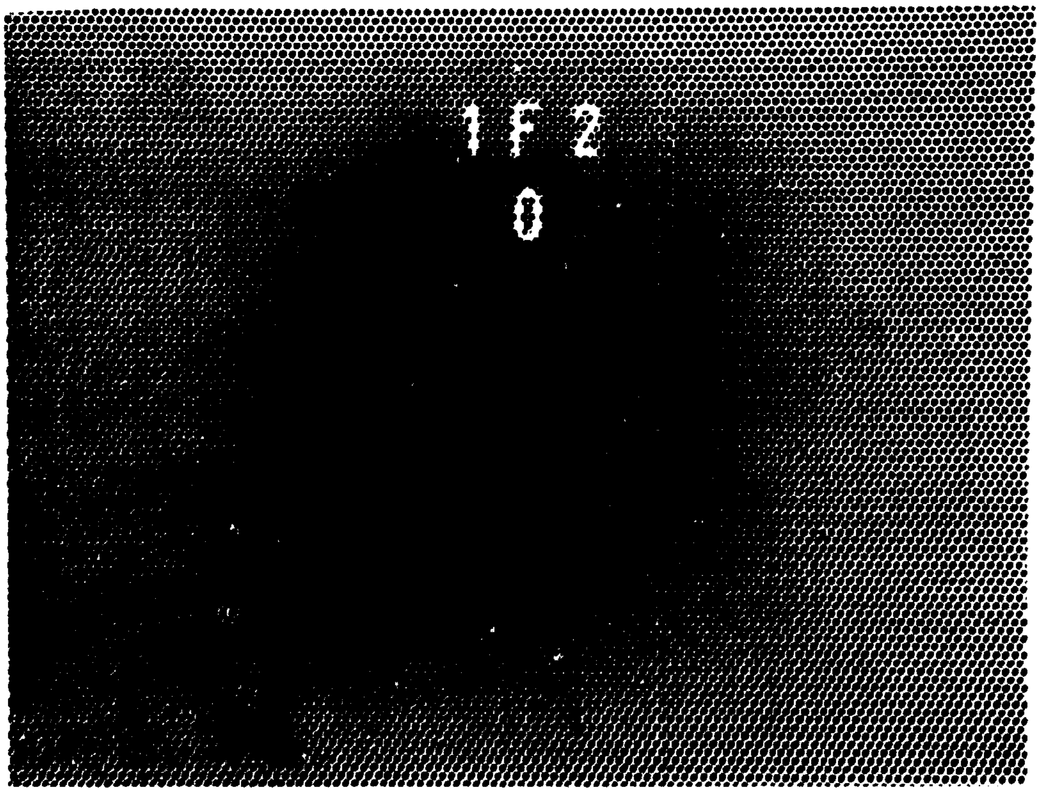

Fig. 93. As fig. 92. Old Kodak 30 x 40 cm cassette with intensifying screen.

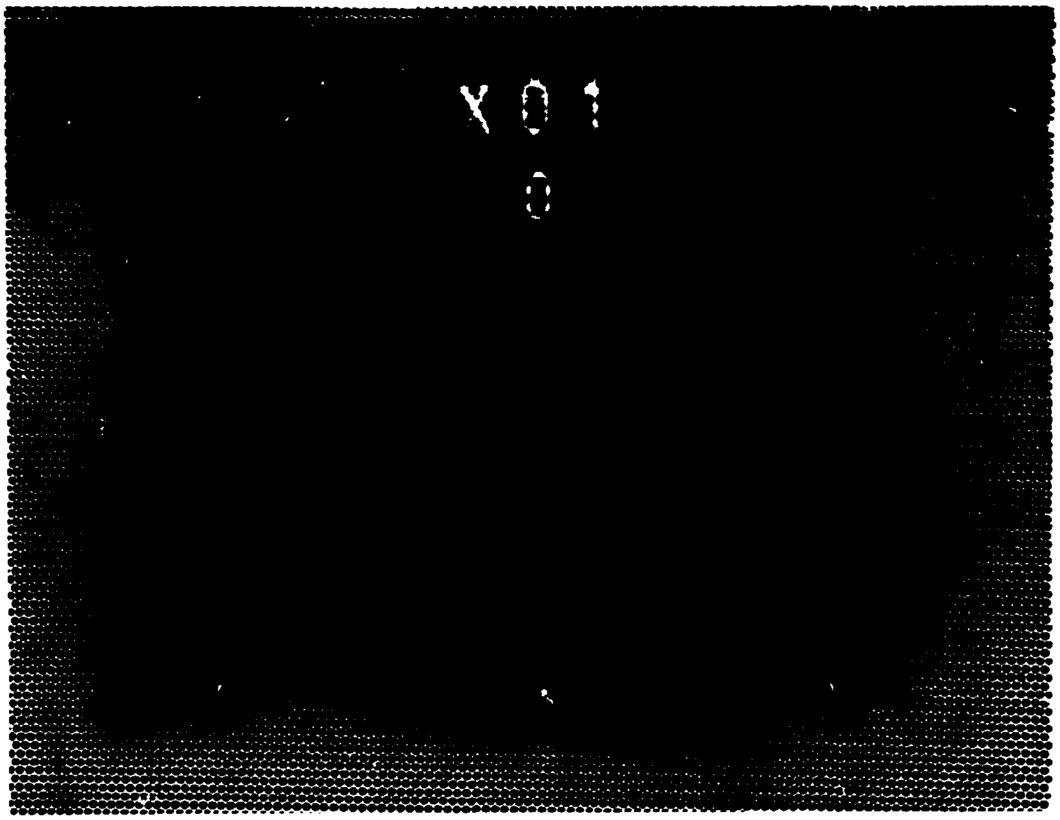

Fig.94. As fig.92. Old Kodak 30x40 cm cassette with intensifying screen

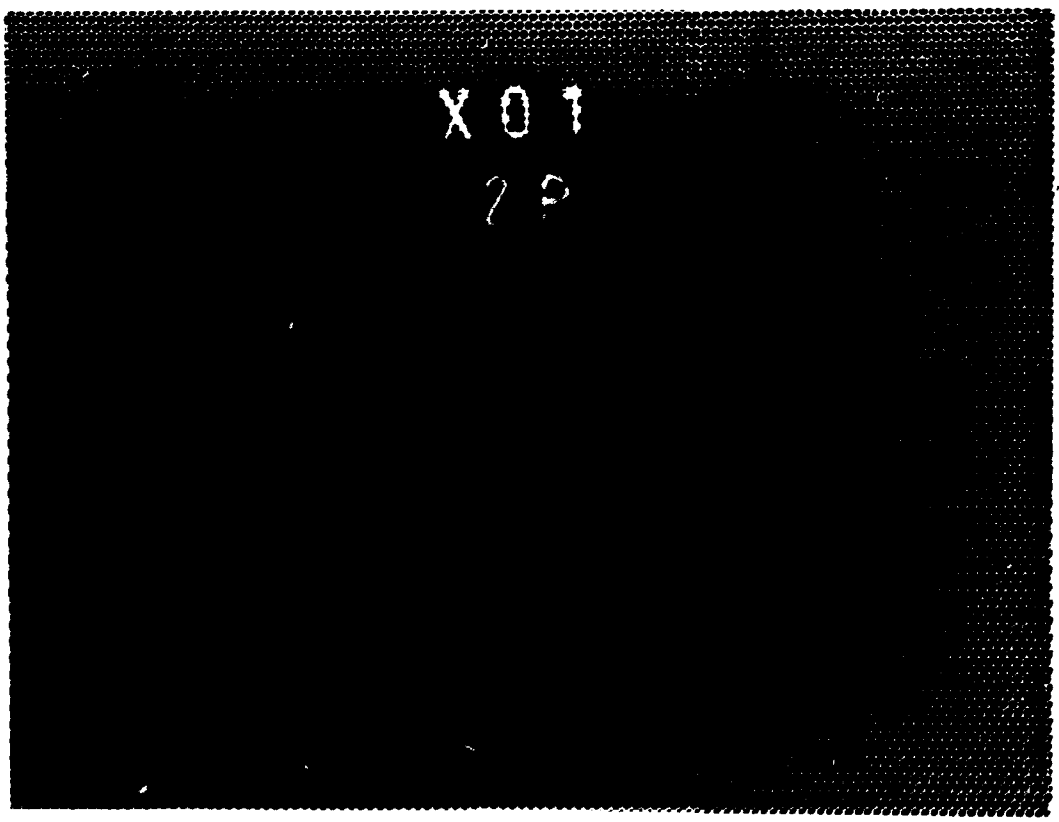

Fig. 95. As fig. 92. Old Kodak 30 x 40 cm cassette with intensifying screen. Two layers of paper between the lid and radiographic paper.

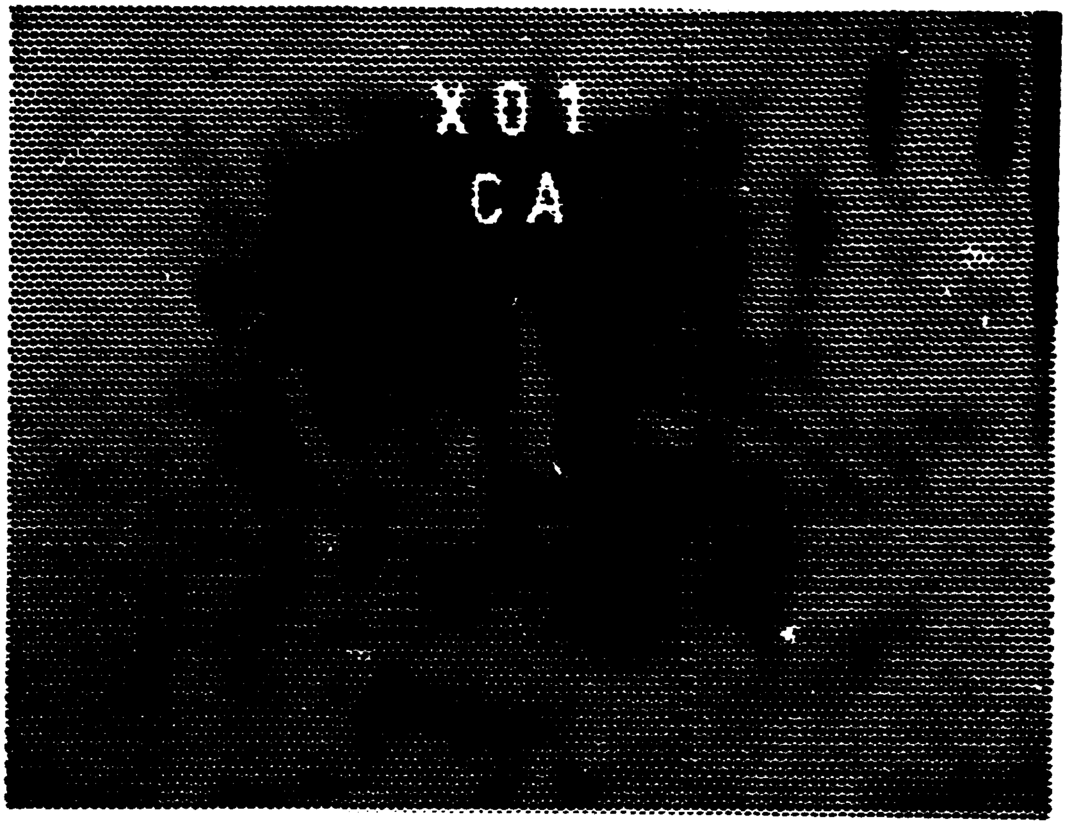

Fig. 96. As fig. 95. A cardboard sheet between the lid and radiographic paper.

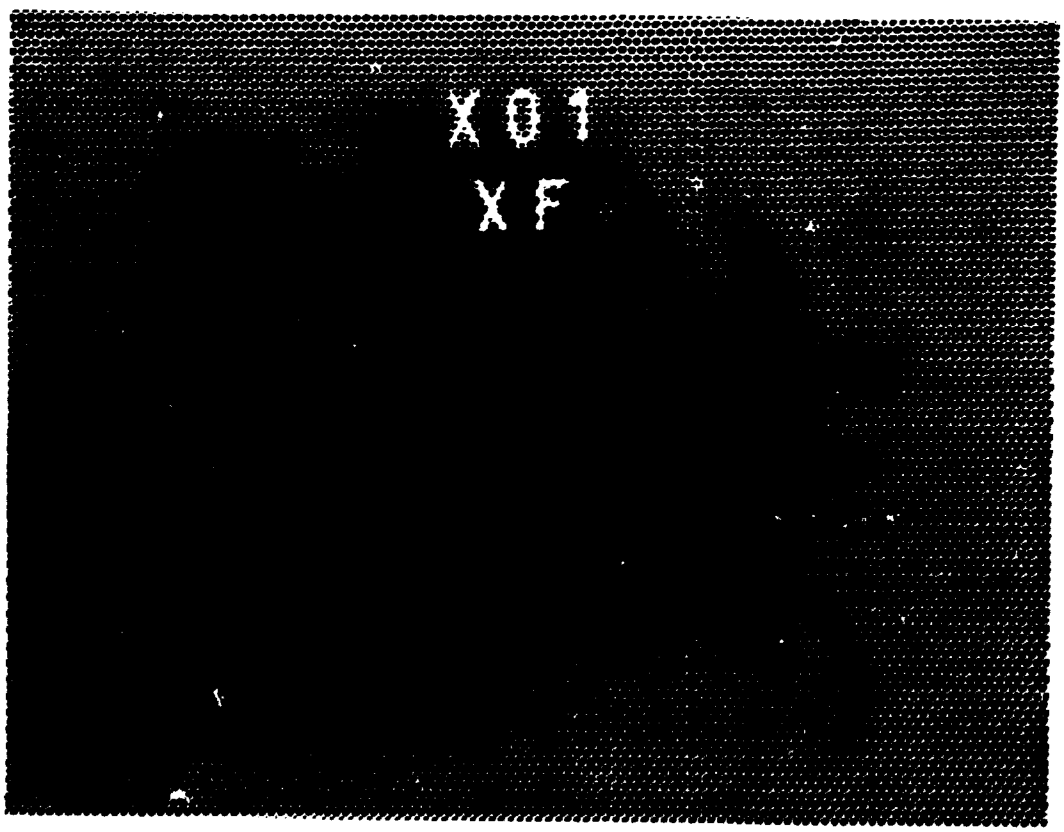

Fig. 97. As fig. 95. An X-ray film between the lid and the radiographic paper.

central area of the picture. Obviously, this lack of good contact is due to uneven pressure distribution between the lid and the body of the cassette. Therefore an attempt was made to equalize this pressure by inserting some additional material between the lid and the radiographic paper. Figure 95 shows the results obtained with two layers of paper, fig. 96 with a sheet of cardboard, and fig. 97 with a sheet of ordinary X-ray film.

With the less robust Cawo cassettes, the best results were obtained by inserting a plastic bag with some air in it between the lid and the radiographic paper. This method was also tried on the Kodak 30 x 40 cm cassettes, but the results were not as good as with the Cawo cassettes. Figure 98 shows a picture taken with such an air bag.

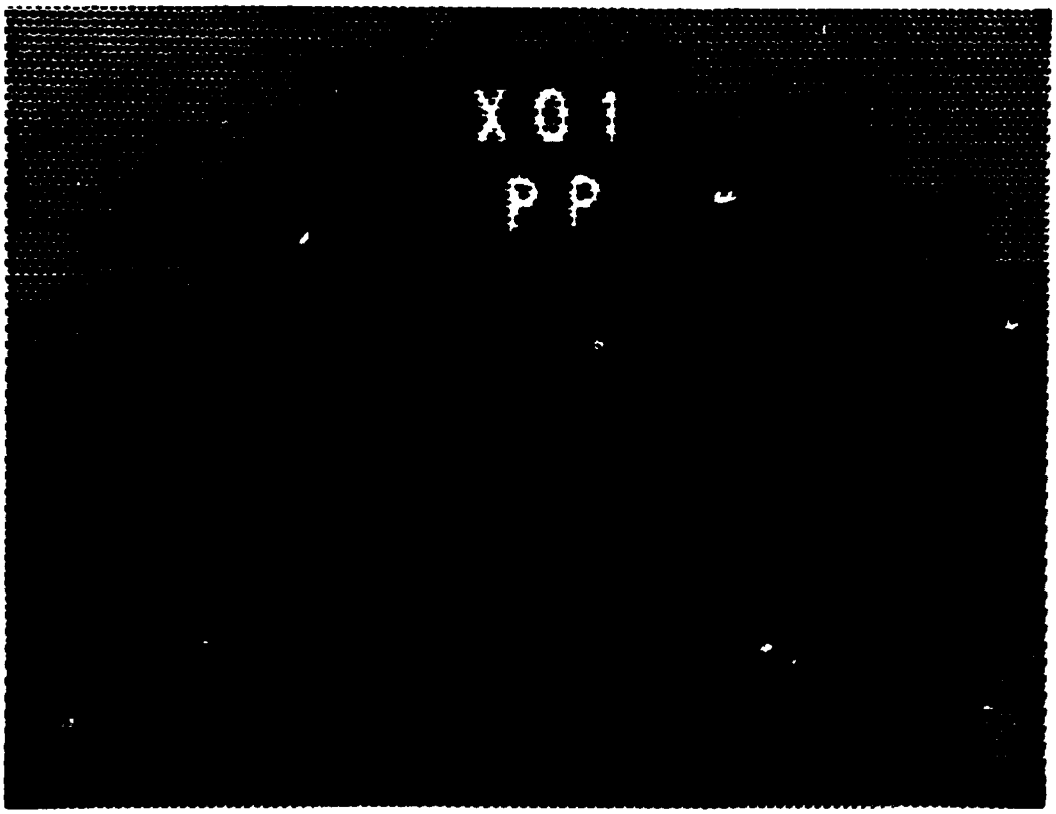

Fig. 98. As fig. 95. An air bag between the lid and radiographic paper.

As mentioned before, the best results were obtained during radiography of thicker sections of U/Al, Fe or Al specimens, if a thin lead filter was present at the top of the cassette. Therefore a 0.05 mm thick Pb filter was permanently placed in the 30 x 40 cm cassette between the front wall of the cassette and the intensifying screen. This lead filter improved the contact between the paper and the screen.

The contact between the radiographic paper and the intensifying screen was also poor in the Cawo cassettes. This contact could be considerably improved by inserting into the cassette (between the lid and the radiographic paper) a plastic bag containing a small amount of air (just sufficient to assure an even distribution of pressure in the cassette). Figure 99 shows such plastic bags used in the cassettes.

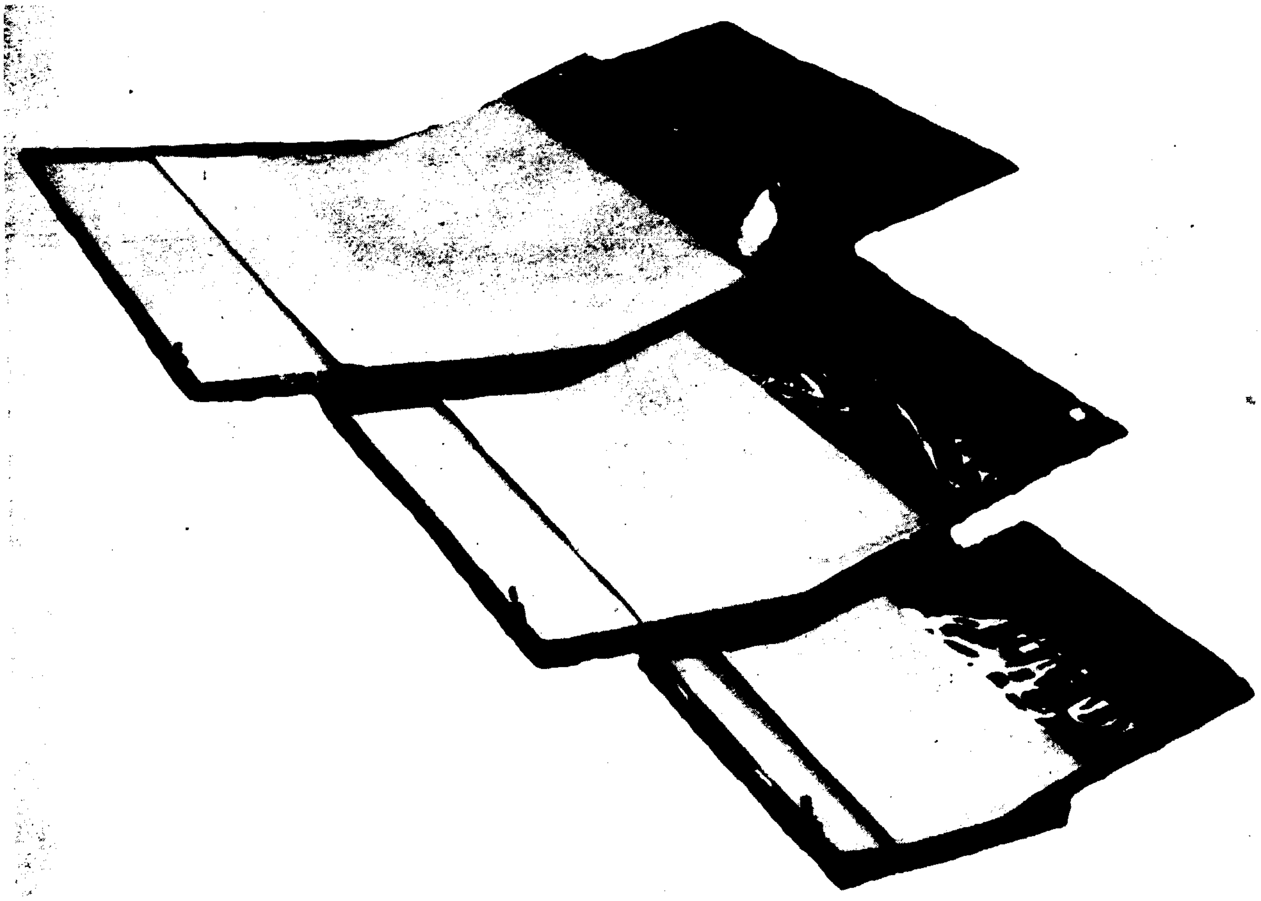

Fig. 99. Pressure equalizing plastic bags (with air inside) used in rigid cassettes between the lid and radiographic paper.

The following pictures illustrate the efficiency of these plastic air bags. Figure 100 shows a grid picture taken in a 18 x 24 cm Cawo cassette without a bag and fig. 101 with a bag. Similar results were obtained with a Cawo 30 x 40 cm cassette. In one of these cassettes, a 0.05 mm lead filter is permanently fixed under the front wall of the cassette. Also here a plastic bag is used.

The problem of correct contact is especially acute in the large 50 x 60 cm Cawo cassettes. Figure 102 shows the grid picture taken in such a cassette. The very poor contact between the paper and the screen resulted from several factors. The first factor contributing to the unusually serious unsharpness was the discrepancy between the size of the radiographic paper and the internal dimensions of the cassette. The 50 x 60 cm Cawo cassette has internal dimensions of 502 x 602 mm. The radiographic paper should have dimensions that are smaller than nominal size of the cassette. For X-ray films, screens and cassettes, several national standards[25,26,27] state requirements for the film, screen and cassette sizes. Unfortunately, no such standards exist for radiographic paper. However, radiographic paper and X-ray film are entirely analogous in this respect. The standards in question require that the internal dimensions of the cassettes should be larger than the nominal size (2 mm larger is required by DIN 54112) and that X-ray film (and hence radiographic paper) sizes should be smaller than the nominal size (2 mm smaller according to the same standard). Table 30 reproduces these requirements from the German standard[27].

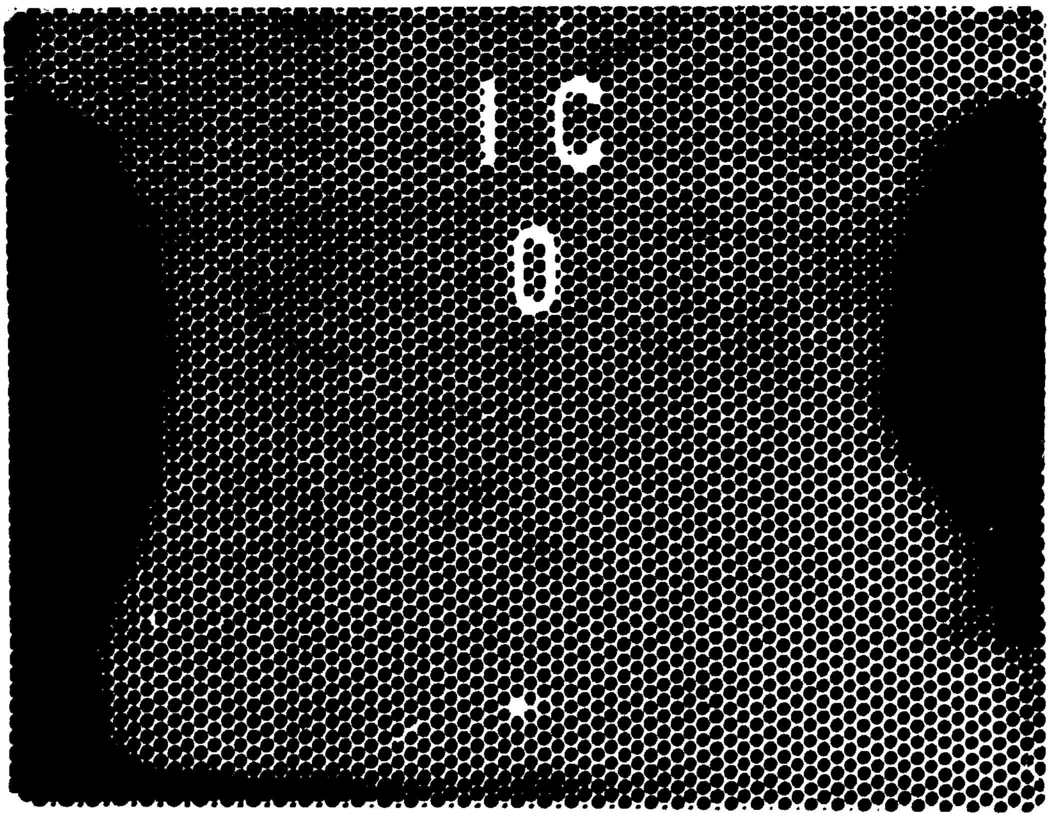

Fig. 100. X-ray picture of a steel grid taken in Cawo 18 x 24 cm cassette.

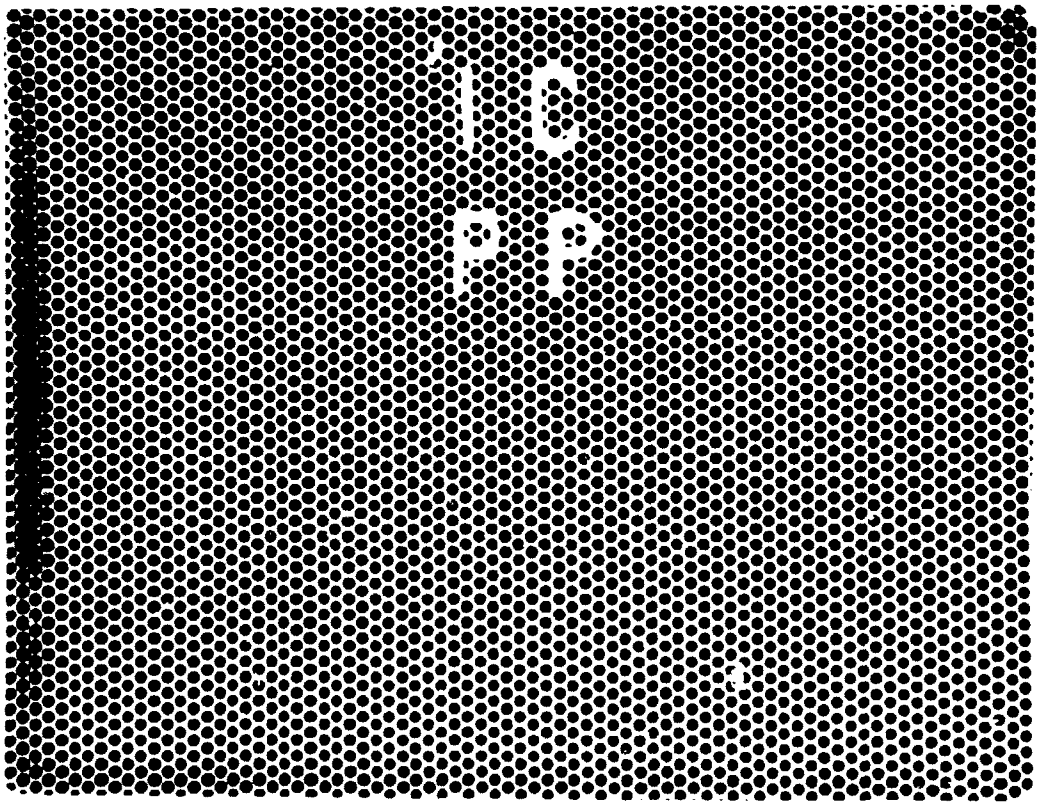

Fig. 101. As fig. 100, with air bag.

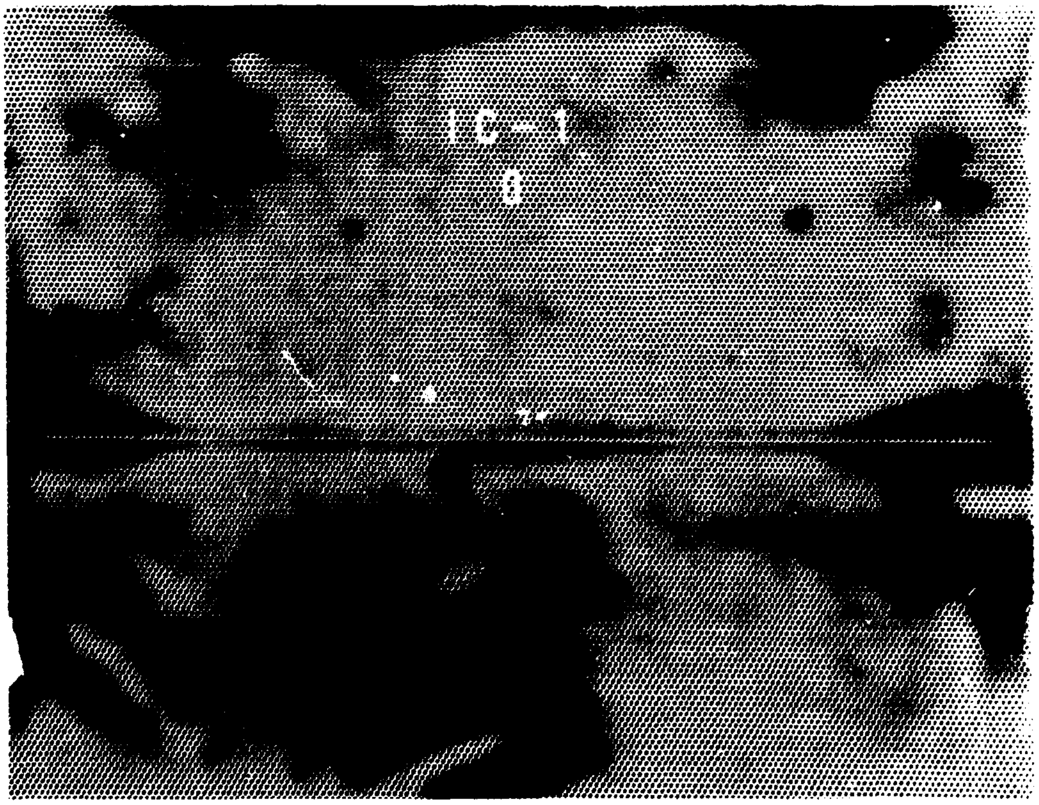

Fig. 102. As fig. 100, for a 50 x 60 cm cassette.

Table 30

Radiography	Nominal size cm	Films mm	Screens mm	Cassettes - mm Metal	Rubber
General	13x18	128x178	130x180	132x182	
	18x24	178x238	180x240	182x242	
	24x30	238x298	240x300	242x302	
	15x40	148x398	150x400	152x402	
	30x40	298x398	300x400	302x402	
Welding	6x24	58.5x238	60x240	61x242	70x300
	6x48	58.5x478	60x480	61x482	70x540
	6x72	58.5x716	60x720	61x724	70x780
	10x24	98.5x238	100x240	101x242	110x300
	10x48	98.5x478	100x480	101x482	110x540
	10x72	98.5x716	100x720	101x724	110x780

Neither in the BS nor in the DIN standard can a nominal size of 50 x 60 cm be found, but one may assume that the same size requirements should apply here, too. As mentioned before, the internal dimensions of the Cawo 50 x 60 cm cassette were in accordance with the standards. Unfortunately, the Agfa-Gevaert IC paper had dimensions not smaller but larger than the nominal size. The 50 x 60 cm paper was actually 503 x 602 mm in size. This oversize was the main reason for the very poor contact between the paper and the screen (as shown on fig. 102), because the paper was bent inside the cassette. This problem was first solved by cutting the paper to the correct size before use, and then the Agfa-Gevaert factory supplied us with the 50 x 60 cm paper cut to the 500 x 600 mm size.

Figure 102 shows another irregularity in a radiographic picture. A white line appears in the middle of the picture along the long axis of the cassette. This was because the Agfa-Gevaert Structurix IC screen type II cannot be supplied in the 50 x 60 cm (although it figures in the Agfa-Gevaert product range - see fig. 103), thus the 50 x 60 cm cassette had to be supplied with two 25 x 60 cm intensifying screens glued on to the cassette. This was acceptable in the particular case of MTR fuel plate radiography, as an even number of plates was always examined. However, in other cases the presence of the image of the contact line between two 25 x 60 cm screens on the radiograph can distort the picture of the object under examination.

As mentioned before, the best means to equalize the pressure in the cassette and to assure good contact between the paper and the screen is the use of plastic bags containing a small amount of air. These plastic bags are placed in the cassettes between the lid and the paper. Figure 104 shows the effect of this technique on the sharpness of a 50 x 60 cm paper radiograph of a steel grid. The unsharpness appearing along the longitudinal axis of the cassette results from the joint between the two 25 x 60 cm screens and cannot be avoided.

Figure 99 shows plastic bags for 18 x 24, 30 x 40 and 50 x 60 cm cassettes. It must be emphasized that the amount of air contained in the plastic bag must be individually adjusted to each type and size of cassette.

Product range

Structurix IC paper
13 × 18 cm (100 sheets)
18 × 24 cm (100 sheets)
24 × 30 cm (100 sheets)
30 × 40 cm (100 sheets)
10 × 48 cm (150 sheets)
50 × 60 cm (100 sheets)
4½ × 17 in (150 sheets)
8 × 10 in (150 sheets)
14 × 17 in (150 sheets)

Structurix IC screens Type II
13 × 18 cm (1 screen)
18 × 24 cm (1 screen)
24 × 30 cm (1 screen)
30 × 40 cm (1 screen)
10 × 48 cm (1 screen)
50 × 60 cm (1 screen)
4½ × 17 in (1 screen)
8 × 10 in (1 screen)
14 × 17 in (1 screen)

Structurix IC cassettes (aluminium)
13 × 18 cm (1 cassette)
18 × 24 cm (1 cassette)
24 × 30 cm (1 cassette)
30 × 40 cm (1 cassette)
10 × 48 cm (1 cassette)
50 × 60 cm (1 cassette)
8 × 10 in (1 cassette)
14 × 17 in (1 cassette)

Processing units
Structurix IC 35
Structurix IC 50

Chemicals
Activator G 126 (1 litre)
Stabilizer G 326 (1 litre)

Fig. 103. Agfa-Gevaert IC System product range.

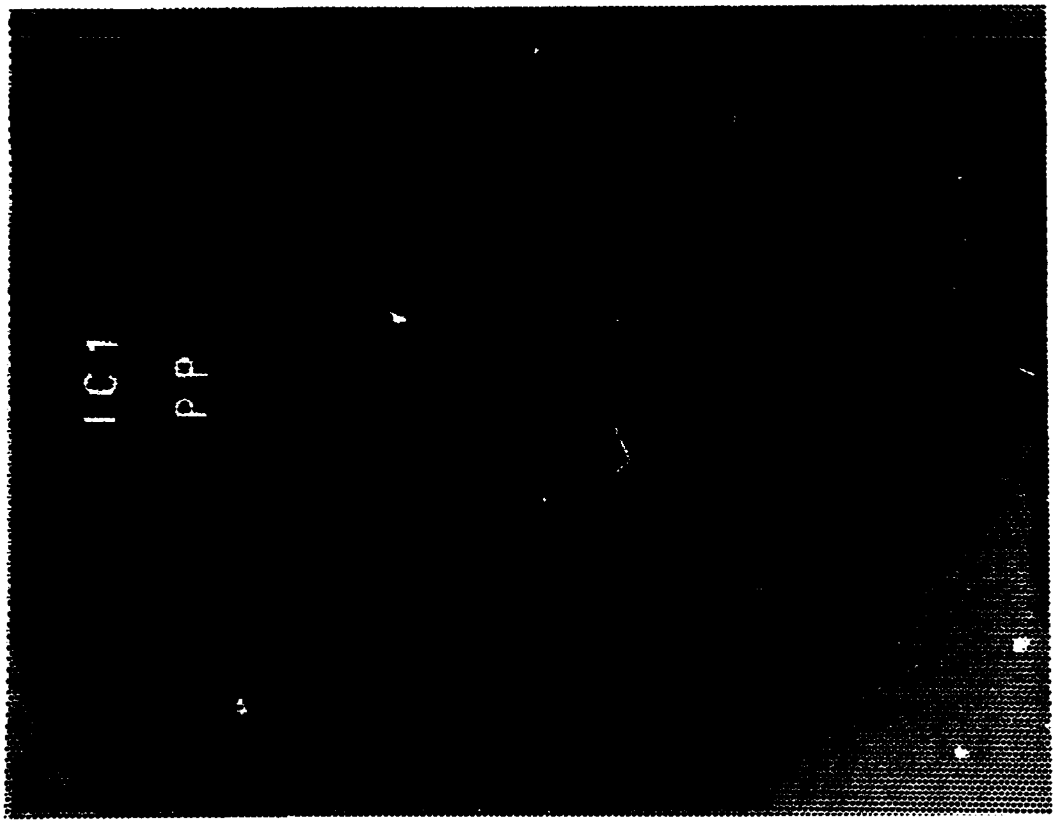

Fig. 104. As fig. 100, for a 50 x 60 cm cassette with plastic bag.

10. INFLUENCE OF PROCESSING AND PAPER-SCREEN COMBINATION ON RELATIVE SPEED AND CONTRAST

Throughout the investigation both the Agfa-Gevaert Structurix IC as well as the Kodak Industrex Instant 600 and 610 papers were used. They were processed in the standard Agfa-Gevaert Structurix IC 50 and the Kodak Industrex Instant Processor Model P 1, as described in 4.2 above. In these processors, Agfa-Gevaert G 126 activator and G 326 stabilizer, or Kodak Industrex Instant Activator and Stabilizer, were used, respectively.

To check the influence of the processing chemicals on the sensitometric properties of the radiographic paper, Kodak paper was processed in Agfa-Gevaert chemicals, and Agfa-Gevaert paper in those of Kodak. The results of this experiment are shown on fig. 105 where A-P stands for Agfa-Gevaert paper Structurix IC, K-P stands for Kodak Industrex 610 paper and A-D and K-D for

Agfa-Gevaert processing or Kodak processing. The IC paper was exposed with IC II as well as XO, F1 and F2 screens, as also the 610 paper. All the characteristic curves shown on fig. 105 were taken at 35 kV (plate No. 516 as filter). From these curves the relative speed and contrast (both at $D_p = 1.0$) were calculated, and they are shown in table 31.

Table 31. Relative speed and contrast for different paper, screen and processing combinations.

Paper	Screen	Processing			
		Agfa- Gevaert		Kodak	
		Relative speed	Contrast	Relative speed	Contrast
IC	IC II	117.8	2.3	96.6	3.3
	XO	100.0	3.0	117.5	4.3
	F1	95.5	4.1	87.1	4.4
	F2	24.0	3.9	26.3	2.7
	O	9.8	0.8	11.0	1.0
610	IC II	112.2	2.5	58.9	2.3
	XO	123.0	2.2	81.3	2.1
	F1	98.9	2.4	55.0	2.5
	F2	24.6	3.1	16.2	2.1
	O	1	1.1	-	-

From the above table, the following conclusions can be drawn:

- When exposed with the Agfa-Gevaert IC II screen, the Agfa-Gevaert IC paper looses its relative speed - but gains in contrast - when processed in Kodak chemicals.
- The same paper exposed with Kodak XO, F1 or F2 screens has almost the same relative speed when processed in Agfa-Gevaert or Kodak chemicals.
- The Kodak 610 paper can reach a higher relative speed when processed in Agfa-Gevaert chemicals (the contrast being almost equal).

When considering these conclusions, it must be recalled that the characteristic curves were taken at 35 kV and that a higher voltages differences in speed and contrast can also differ.

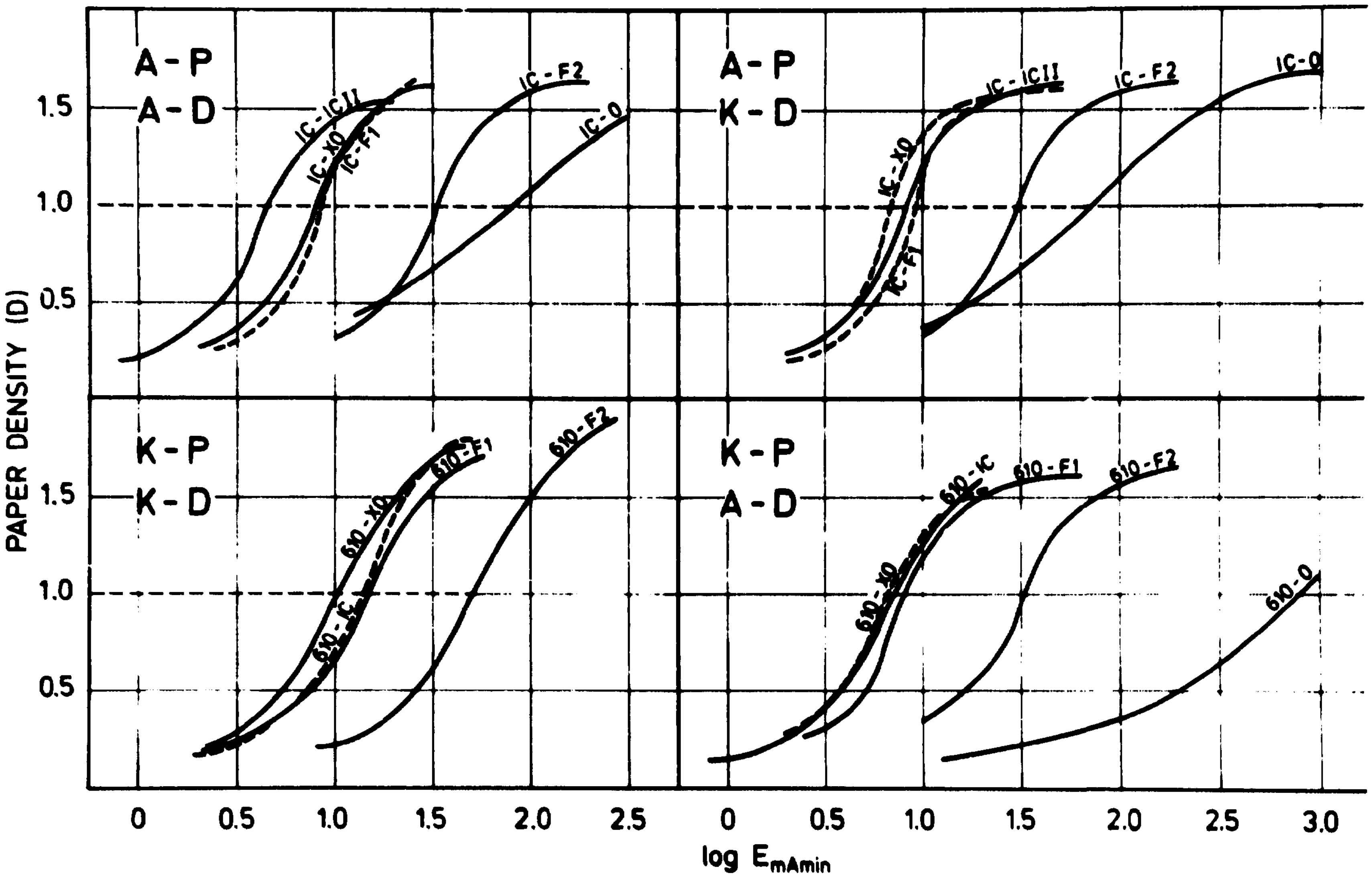

Fig. 105. Characteristic curves of Agfa-Gevaert and Kokak papers processed in different processing chemicals.

Anyway, all combinations of similar paper, screen and processing are possible, and they may be used, if necessary, without risk of considerable deterioration in speed or contrast.

11. CONSISTENCE OF PAPER AND SCREEN QUALITY

Throughout this investigation radiographic paper of different sizes and from different batches was used. Also different sizes of intensifying screens (not purchased simultaneously) and cassettes were used. Therefore, a test was made to determine if similar results can be obtained when radiographs are made using different batches of paper and screen.

The tests were performed using 18 x 24 and 50 x 60 cm Cawo cassettes and intensifying screens and Agfa-Gevaert IC 18 x 24, 30 x 40 and 50 x 60 cm paper. Both the paper and the screens of different sizes were bought at different times, and did not originate from the same production batch.

Figure 106 shows the results of the comparison of characteristic curves, taken at 50 kV, of the IC paper of different sizes (and hence from different batches) exposed with 18 x 24 and 50 x 60 cm screens. As can be seen, there are some differences of relative speed and contrast. These are shown in table 32 (for density D_p = 1.0).

Table 32

Relative speed and contrast of IC paper from different batches exposed with 18 x 24 and 50 x 60 cm IC II screens

Screen size	18 x 24 cm		50 x 60 cm	
Paper size	Relative speed	Contrast	Relative speed	Contrast
18 x 24 cm	1.33	2.3	1.35	1.9
30 x 40 cm	1.17	2.7	1.0	2.4
50 x 60 cm	1.48	2.3	1.45	2.1

The same characteristic curves as on fig. 106 are shown on fig. 107 in such a way that it is posssible to compare the influence of screens from different batches on the speed and contrast of the paper.

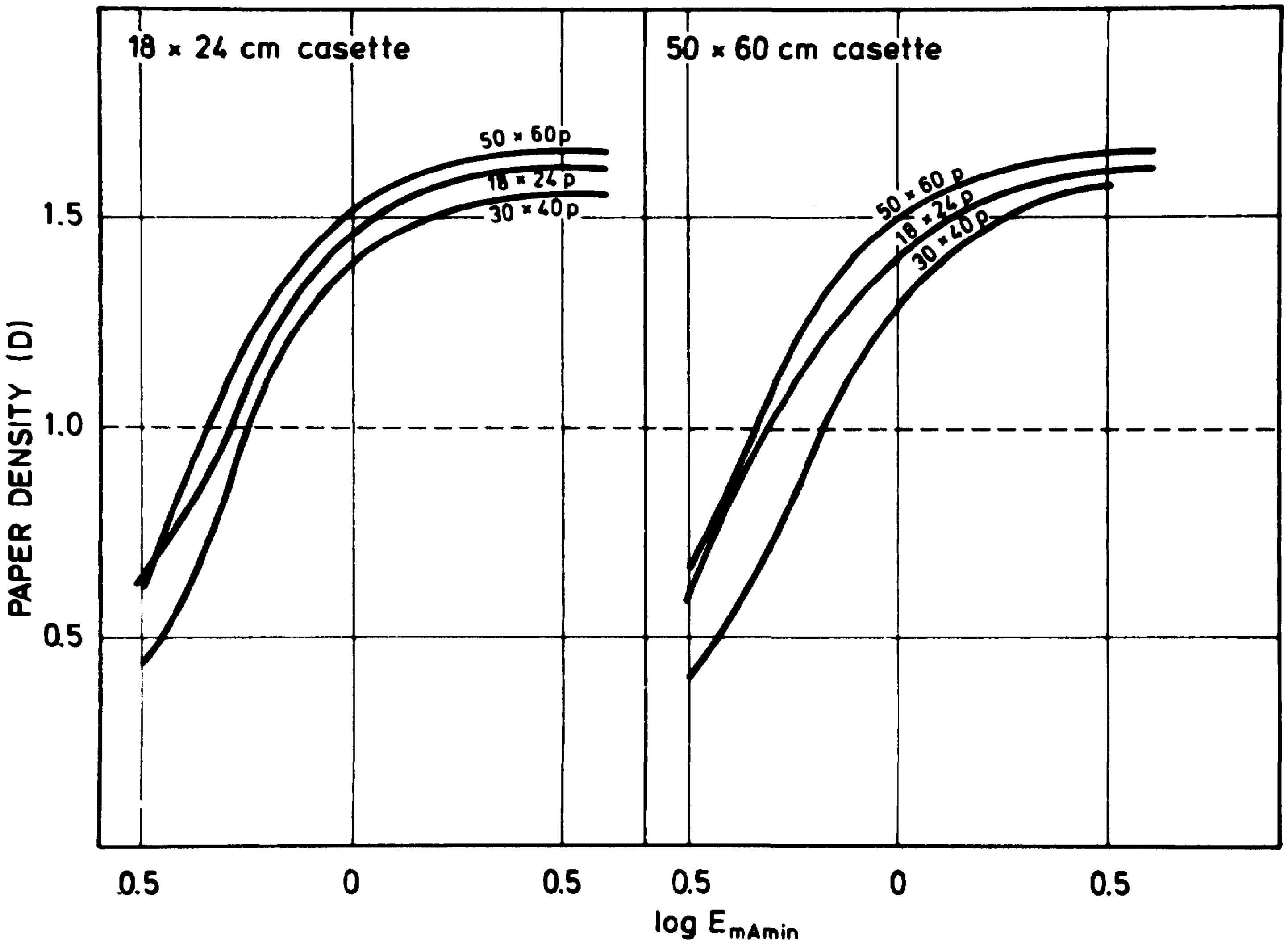

Fig. 106. Characteristic curves of the IC paper from different batches exposed with 18 x 24 and 50 x 50 cm IC II screens.

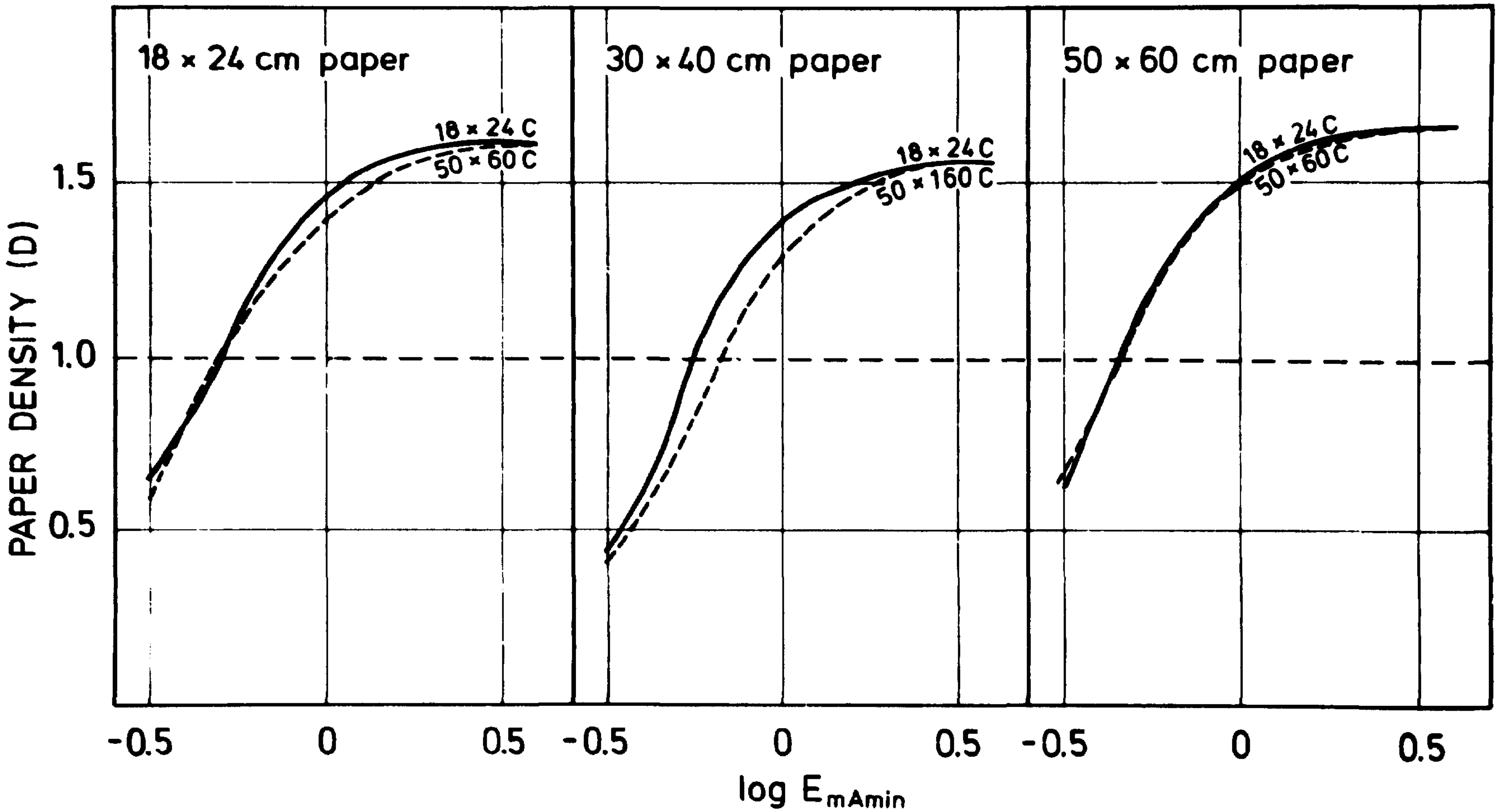

Fig. 107. As fig. 106.

As can be seen, screens from different batches give more consistent results than paper from different batches.

Using paper from different batches with the same screen, differences in relative speed can be as great as 45%, whereas when using screens from different batches with the same paper, only a relative speed variation of 17% was observed.

12. THE PRACTICAL APPLICATION OF PAPER RADIOGRAPHY

At the Risø National Laboratory radiography is mainly used for the control of nuclear fuel elements. Several examples of the practical application of paper radiography are therefore taken from this field.

As mentioned at the beginning of this report, the immediate reason for introducing paper radiography was the possibility of obtaining cheaper, faster radiographic control of MTR fuel elements. Once paper radiography was introduced at Risø (with all necessary equipment such as processor and intensifying screens), it was possible to use it to solve other problems, too.

Below, some examples are given of the application of radiographic paper to the control of castings, weldings, solderings and other assemblies as well as in some other fields.

It must be noted that all the radiographs reproduced in this report are of poorer quality than the original ones. This is because it is impossible to reproduce radiographs in publications without losing much of their quality.

12.1. Radiography of castings

Usually casting defects are much larger and less critical than defects in weldings. Therefore, paper radiography can well be used in this field.

Figure 108 shows a paper radiograph taken at 150 kV of a 18.5/20 mm thick cast iron grid in which porosities can be seen. An IQI sensitivity of better than 2% could be reached.

Figure 109 reproduces a radiograph of a 30 mm thick aluminium casting. It was taken at 50 kV with a beryllium-window X-ray tube. Porosities in the casting can be easily detected. The use of a conventional IQI, in which the Al wires are em-

Fig. 108. Radiograph of a 18.5/20 mm thick cast iron grid taken at 150 kV. A 0.05 mm Pb filter at the cassette.

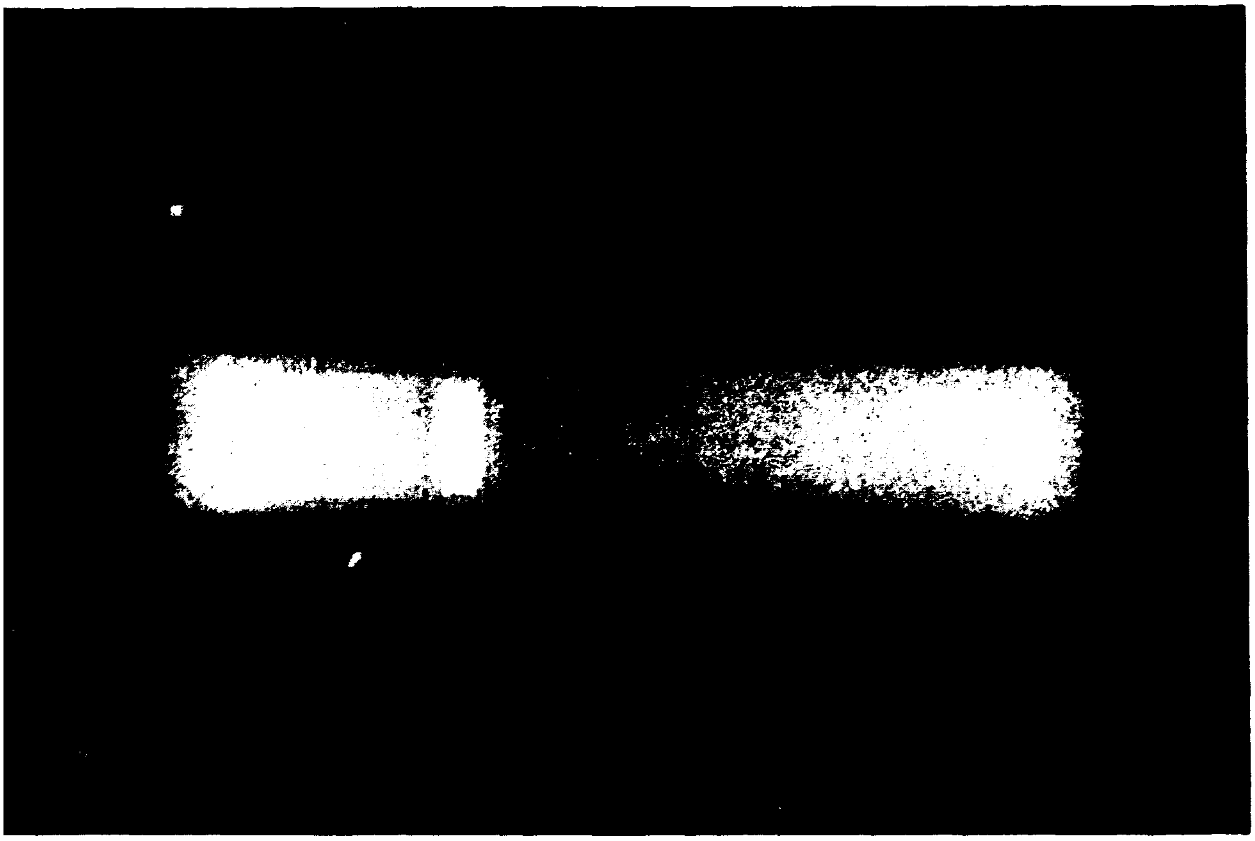

Fig. 109. Radiograph of a 30 mm thick Al casting taken at 50 kV with a beryllium window X-ray tube.

bedded in plastic foil, cannot be recommended, because at low voltages and with soft X-rays, this plastic is seen on the radiograph and blurs the image of the IQI. Nevertheless, an IQI sensitivity of better than 2% can be reached even with a conventional IQI.

As mentioned earlier, the main application of paper radiography at the Risø National Laboratory is for the control of nuclear fuel elements. Figure 110 shows a radiograph of a 30 mm thick uranium-aluminium casting from which the MTR fuel plates are produced. Here it was impossible to use a standard IQI, as wires from U/Al alloys are not available. Therefore a special IQI was produced. It consists of a 30 mm U/Al block at the top of which 5 circular holes were drilled, having diameters corresponding to 5, 3, 2, 1.67 and 1.33% of the block thickness. On the radiographs, the third hole can be clearly seen, which means that a 2% IQI sensitivity is reached.

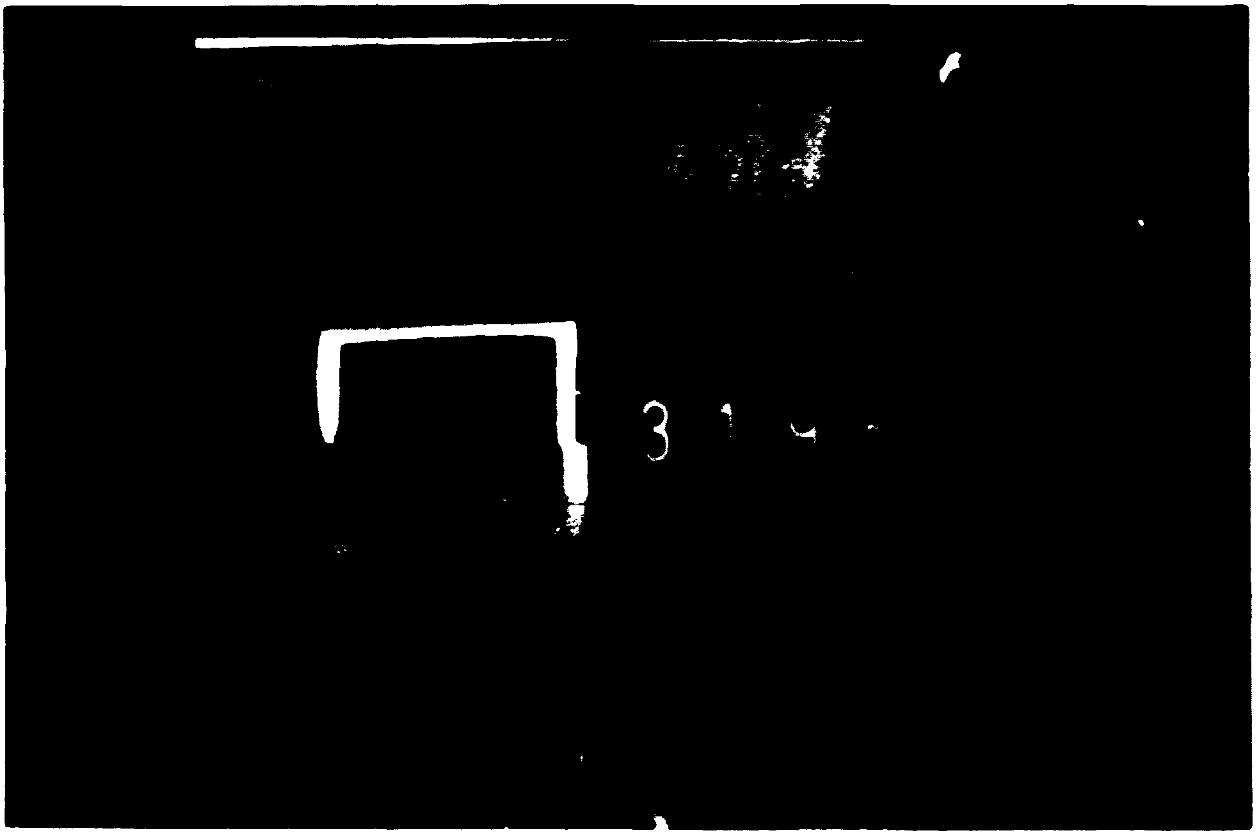

Fig. 110. Radiograph of a 30 mm thick U/Al casting taken at 150 kV. A 0.05 mm Pb filter at the cassette.

12.2. Radiography of U/Al rolled plates

From 30 mm U/Al blocks, 0.5 mm thick cores for MTR fuel plates are rolled down[12]. These cores are thereafter sandwiched between two 0.5 mm thick aluminium plates. Radiographic control takes place after this operation. The aim of this control is two-fold: to check the homogeneity of the uranium distribution in the U/Al core and to check the positioning of the core inside the aluminium plates. To obtain best results during homogeneity control, rather soft X-radiation is needed, because the difference between the attenuation coefficients for U and Al is greatest here.

Figure 111 shows a radiograph of two U/Al MTR fuel plates taken at 30 kV with a beryllium window X-ray tube. The white areas on the radiograph result from a higher concentration of uranium in the plate.

As explained in 12, 21, 23) an aluminium step wedge is used to control the radiographic quality of fuel plates. At 30 kV,

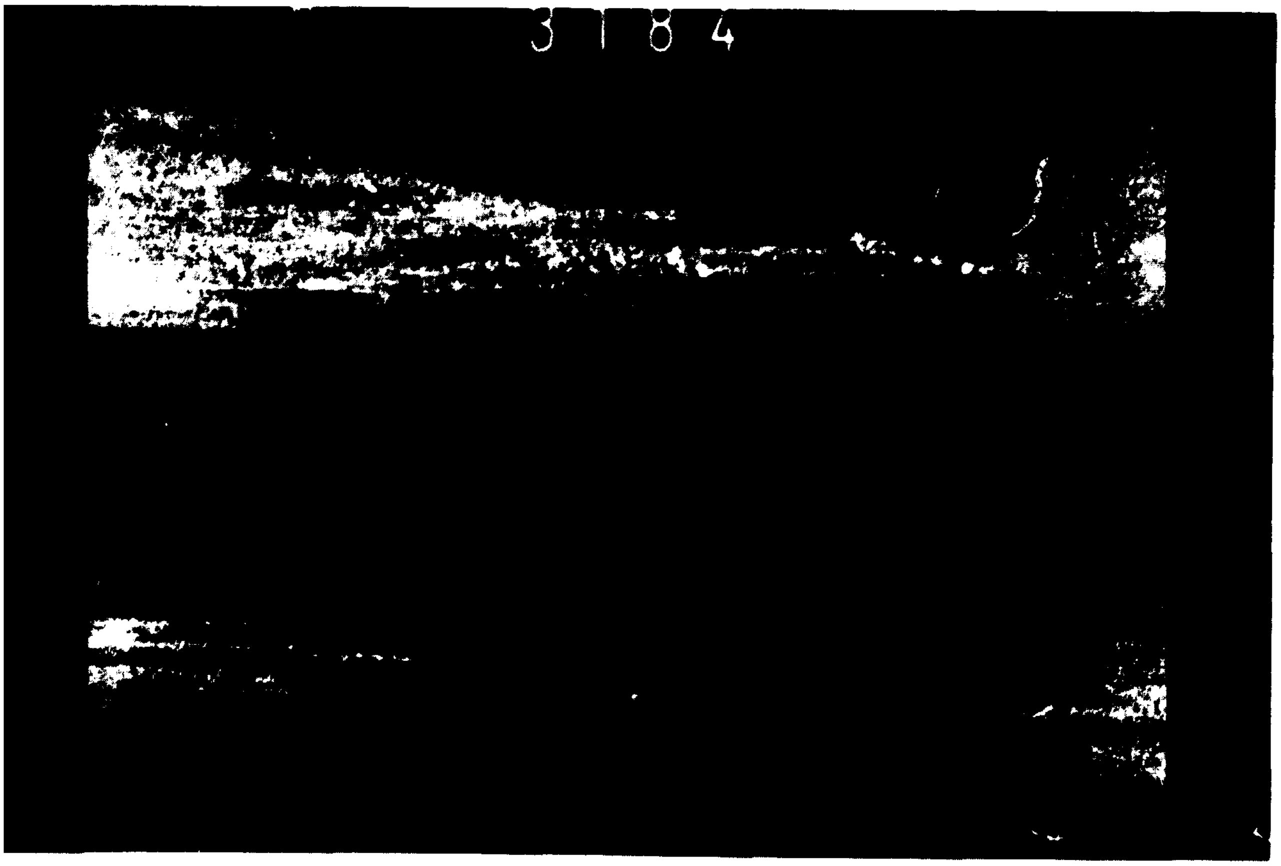

Fig. 111. Radiograph of a 1.5 mm thick U/Al plate taken at 30 kV with a beryllium window X-ray tube.

at which the radiograph shown on fig. 111 was taken, the Al equivalent of the U/Al plate lies at about 4 mm Al[12)]. Therefore a step wedge ranging from 3.5 to 4.5 mm Al was used. On the radiograph, all the 11 steps (increment of 0.1 mm) can be clearly seen. A density difference of 0.07 per 0.1 mm of Al can be observed at the middle of the step wedge (4.0 mm of Al). Using the formula specified in 23) for the assessment of the radiographic quality of this picture, one finds:

$$\Delta D_{\%} = \frac{D_{3.5} - D_{4.5}}{D_{4.0}} \cdot 100 = \frac{1.26 - 0.69}{1.05} \cdot 100 = 54.3\%$$

At 30 kV a radiograph with a high contrast of the U/Al core can be obtained. Due to this high contrast, the positioning of the core inside the Al plates can hardly be seen. Therefore, a radiograph at 50 kV (as shown on fig. 112) is more suitable for this purpose.

According to 12), the Al equivalent of the U/Al plate at this voltage will be about 5.0 mm Al. Therefore, a step wedge of 5.0/5.5/6.0 mm Al was used to control the quality of the radio-

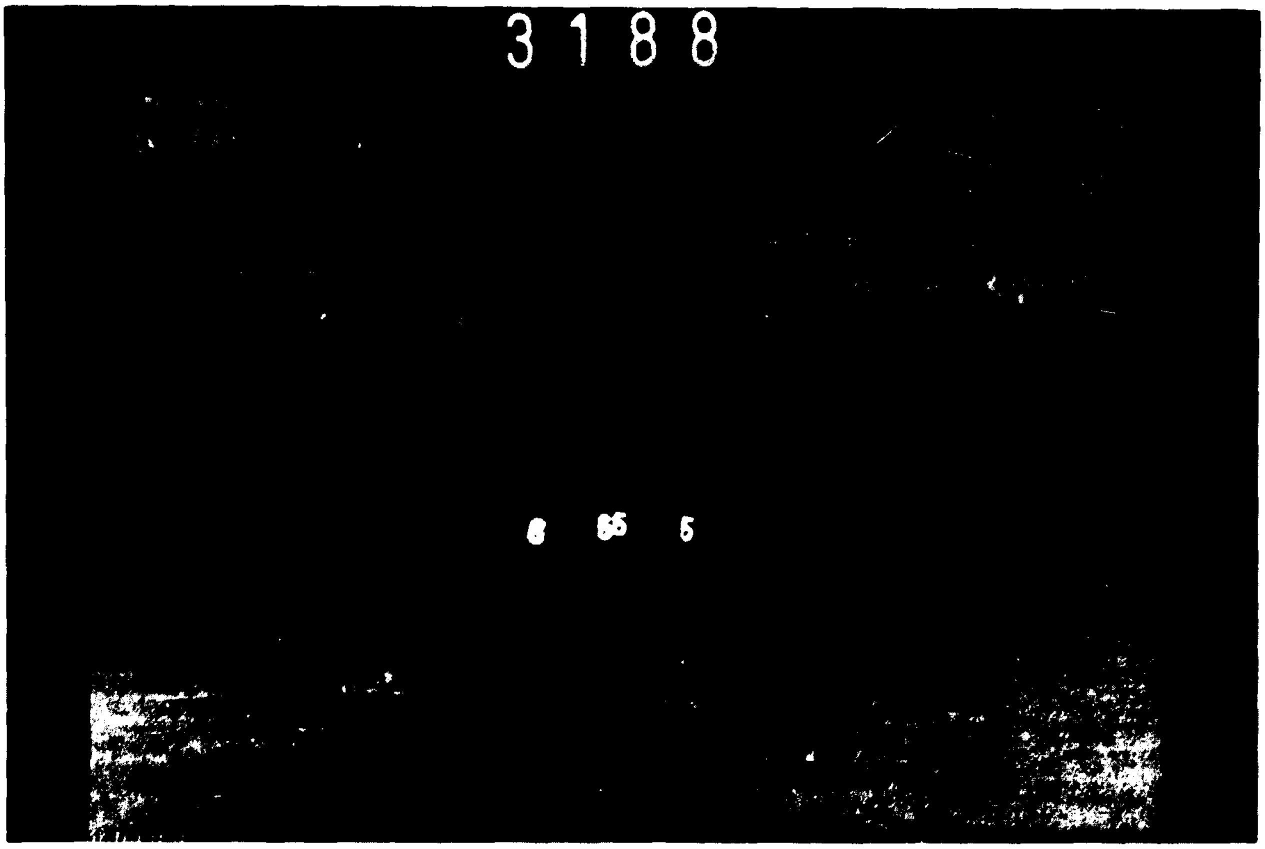

Fig. 112. Radiograph of a 1.5 mm thick U/Al plate taken at 50 kV with a beryllium window X-ray tube.

graphic image at 50 kV. Using the same formula as above[23], the following results can be obtained:

$$\Delta D_{\%} = \frac{D_{5.0} - D_{6.0}}{D_{5.5}} \cdot 100 = \frac{0.72 - 0.59}{0.67} \cdot 100 = 19.4\%.$$

In this case (see fig. 112), the high contrast on the U/Al core was not of such importance as the contrast between the core and the Al plates, between which the U/Al core is sandwiched. A very good contrast in this respect could be obtained using 50kV.

12.3. Radiography of weldings

A review of the literature on the use of radiographic paper was given at the beginning of this report. One of the reports[13] especially concerned the radiography of steel welds. The author recommends that satisfactory radiographs of steel welds can be made using voltages up to 120 kV, at which steel of about 12 mm can be radiographed. The upper limit is said to be 150 kV at which 20 mm of Fe can be radiographed.

Fig. 113. Radiograph of a 5 mm thick steel weld taken at 100 kV. A 0.05 mm Pb filter at the cassette.

On fig. 113 a radiograph of a 5 mm thick steel welding taken at 100 kV is reproduced.

Figure 114 gives an example of a radiograph of a 1.5 mm thick aluminium weld, taken at 25 kV. Porosities in the weld can be clearly seen. As mentioned above, the conventional wire IQI, in which Al wires are embedded in plastic foil, is unsuitable as the plastic obscures the picture of the Al wires.

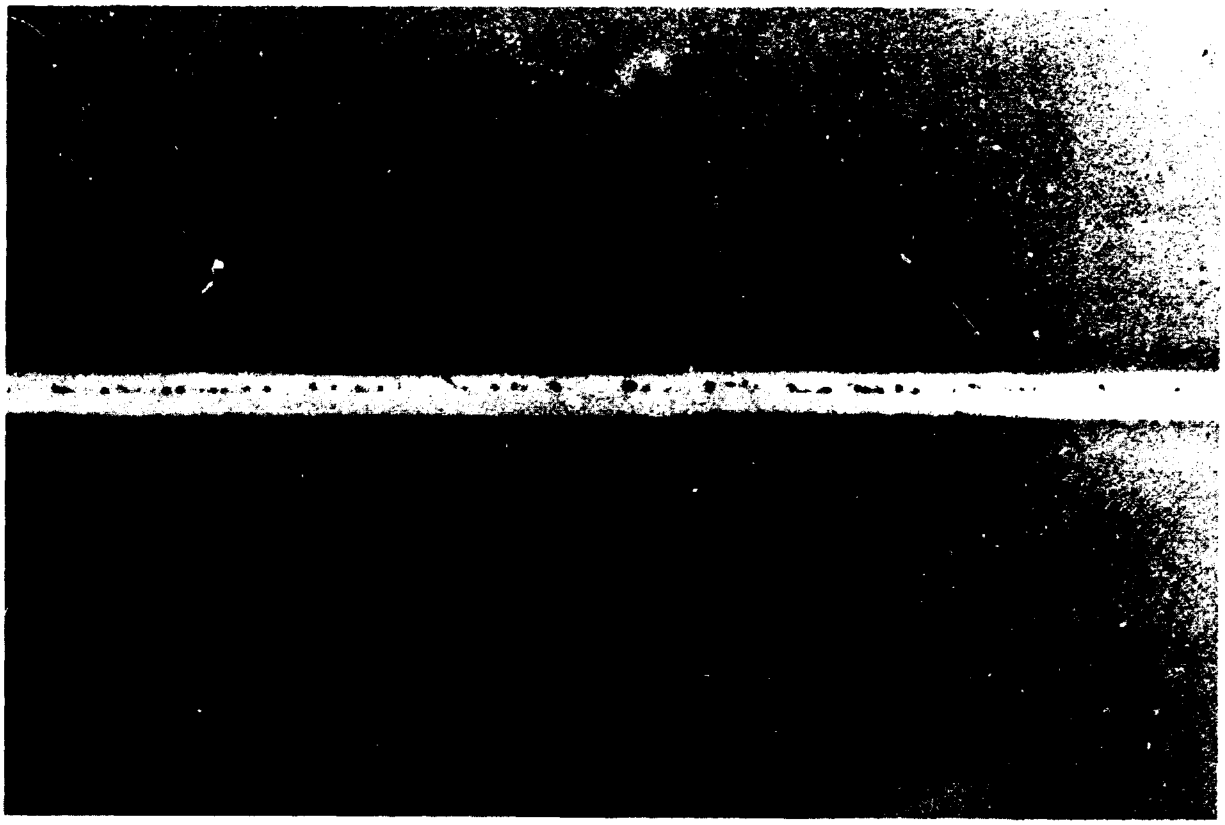

Fig. 114. Radiograph of a 1.5 mm thick Al weld taken at 25 kV with a beryllium window X-ray tube.

12.4. Radiography of solderings

Paper radiography can also be used to control soldered assemblies. Figure 115 gives an example of such an application. On the radiograph taken at 125 kV, three tips of Pitot tubes are shown (used to measure the flying speed of jet aircraft). Imperfect soldering was detected between the outer steel tube of 10.5 mm in diameter and the inner spiral. The radiograph was taken using a 11 mm thick steel masking block in which three holes were drilled to accomodate the Pitot tubes.

Several other examples of radiographic control of aircraft components can be found in 11,15).

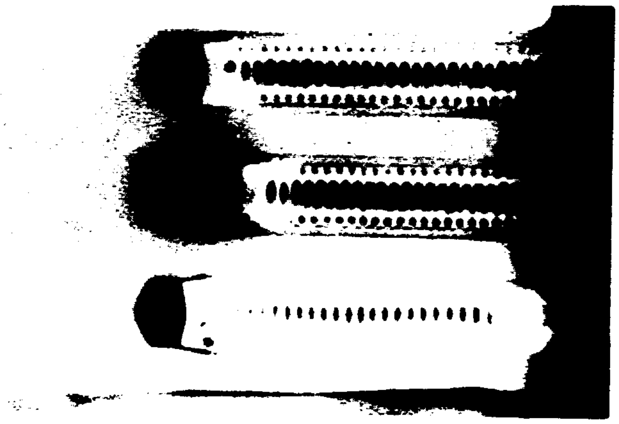

Fig. 115. Radiograph of a 10.5 mm Pitot tube taken at 125 kV.

12.5. Radiography of assemblies

When an object is assembled of several components it is often interesting to know the relative position of these components after the final assembly of the object.

Figure 116 shows a radiograph of a section of anchor chain fished out of the Øresund together with an anchor. Metallurgical investigation showed that the anchor and chain were at least 100 years old[28).

The chain is composed of a wrought iron ring and a cast iron transverse spacer preventing the ring from collapsing when the anchor is pulled up. There was no metallurgical joint between the wrought ring and the cast spacer, as can be seen from fig. 116.

During construction of a cooling installation for a cold neutron source at the DR 3 reactor at Risø, radiography was used to detect the positioning of some internal parts of the assembly. The stainless steel joint (outer diameter 26.6 and wall thickness 3.3/3.7 mm) was first radiographed at 160 kV in close contact to the cassette (see fig. 117). On the radiograph the difference between the left and right parts of the joint can be clearly seen.

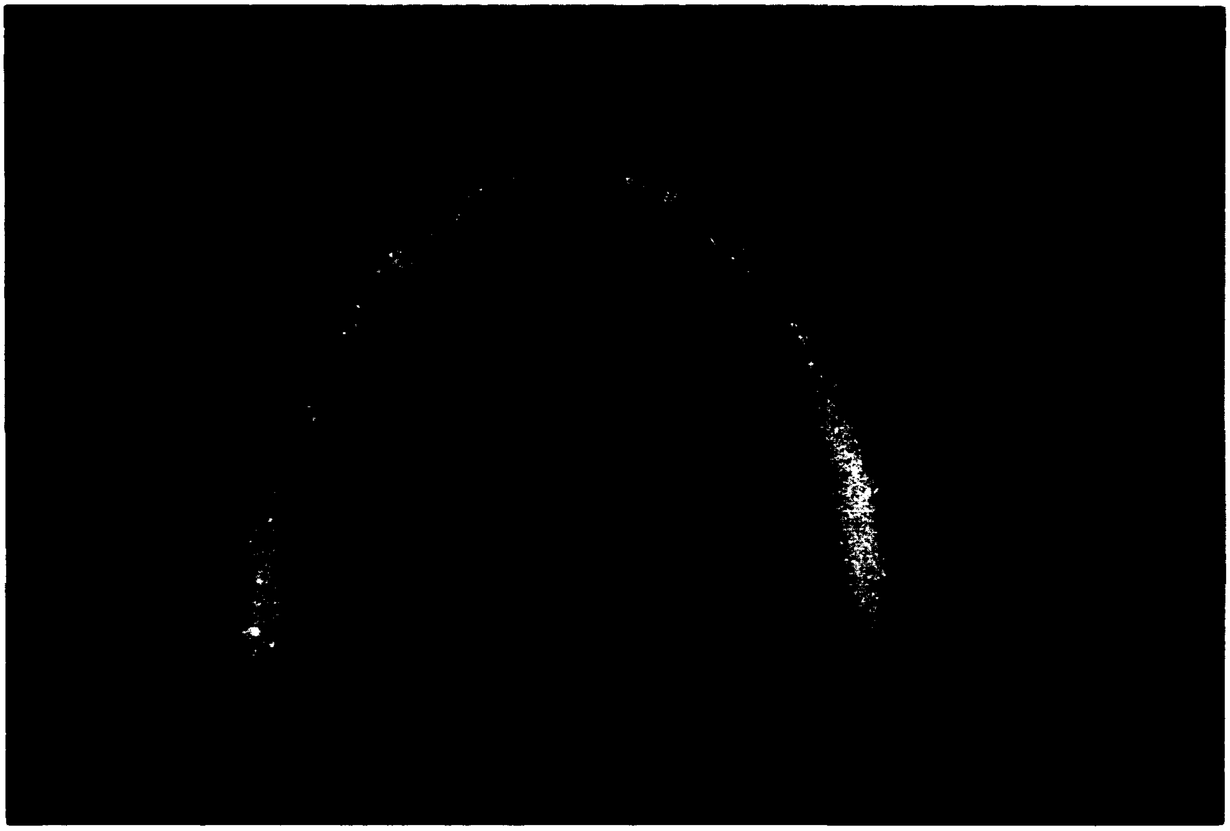

Fig. 116. Radiograph of a 28 mm wrought and cast iron joint taken at 160 kV. A 0.05 mm Pb filter at the cassette.

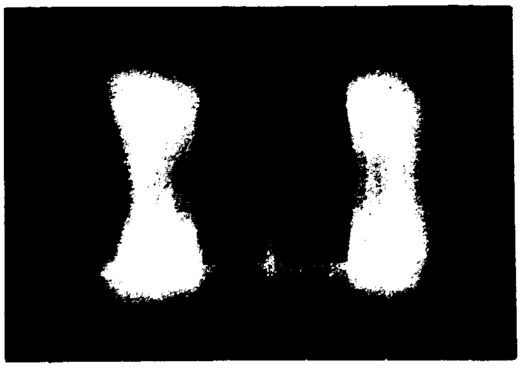

Fig. 117. Radiograph of a stainless steel joint (outer diameter 26.6, wall thickness 3.3/3.7 mm) taken at 160 kV.

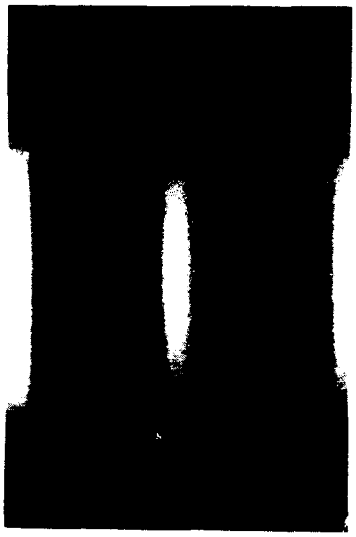

Fig. 118. As fig. 117, but the joint located at a distance from the cassette.

After assembly of the cooling installation, this joint was placed inside a stainless steel tube (3 mm wall thickness) which in turn was surrounded by a corrugated,bellow-like, expansion stainless-steel tube (1 mm wall thickness). The problem was to identify the relative positions of the two parts of the joint inside the two tubes.

First a radiograph was taken of the joint itself, placed at a distance from the cassette corresponding to the position of the joint inside the tubes. On fig. 118 the two different parts of the joint can be clearly seen.

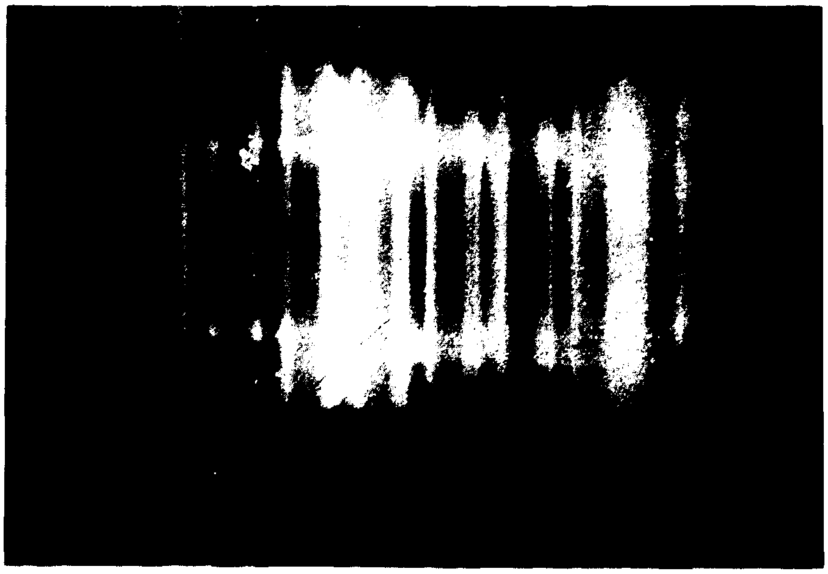

Fig. 119. Radiograph of a stainless steel joint inside two stainless steel tubes taken at 275 kV.

Figure 119 shows the radiograph of the joint inside the two tubes. The relative positions of the two parts of the joint could hardly be seen on the paper radiograph, and the problem was solved by using film radiography. At 275 kV, when using the Kodak Industrex Instant 600 paper with F2 intensifying screens, the exposure time needed was only a tenth of that needed when using the Kodak Industrex M film with 0.1 + 0.15 mm Pb screens.

Another example of the use of paper radiography to control the positioning of internal parts in a closed assembly is given on fig. 120, which shows a radiograph taken at 150 kV of a timer used in the 50 kV Balteau X-ray machine.

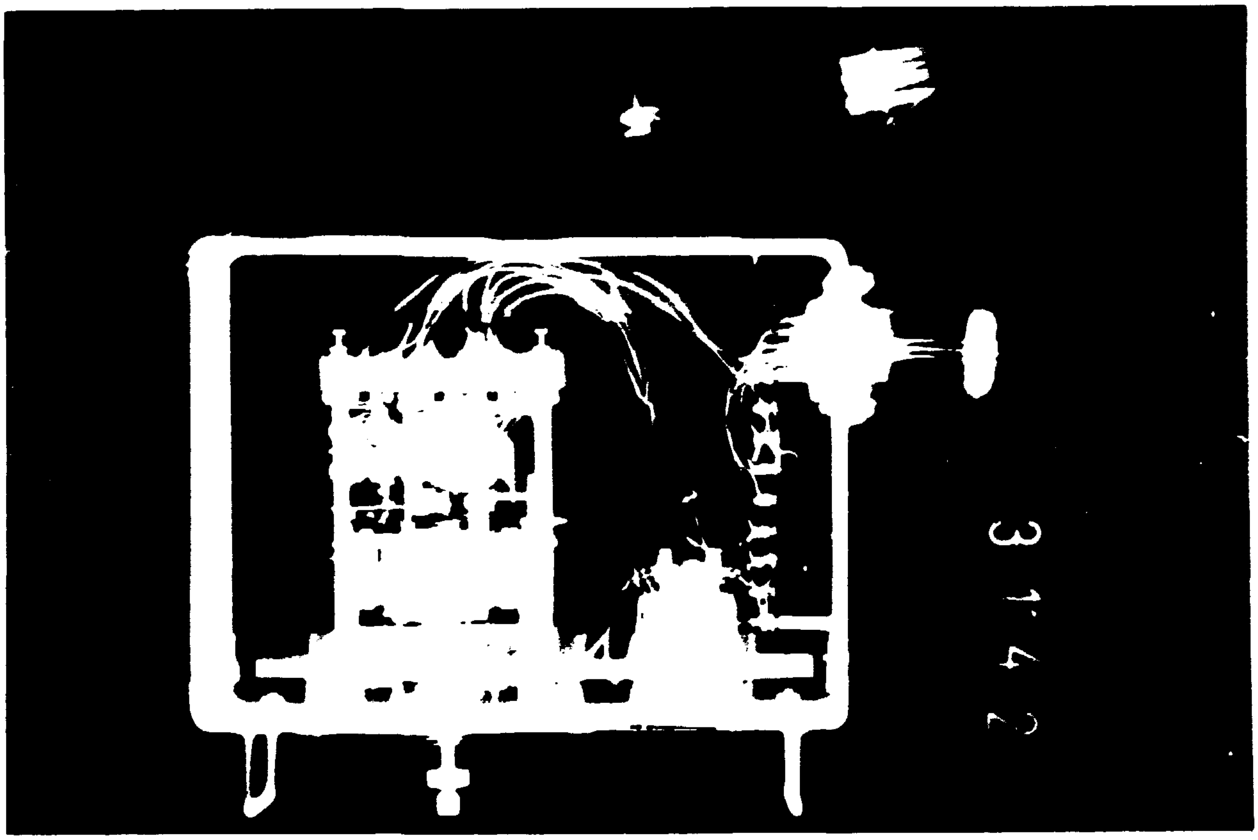

Fig. 120. Radiograph of a timer from the Balteau 50 kV X-ray machine taken at 150 kV.

Paper radiography can control the position and integrity of the heating element (spirals and bimetal control) inside an electric pad (see fig. 121).

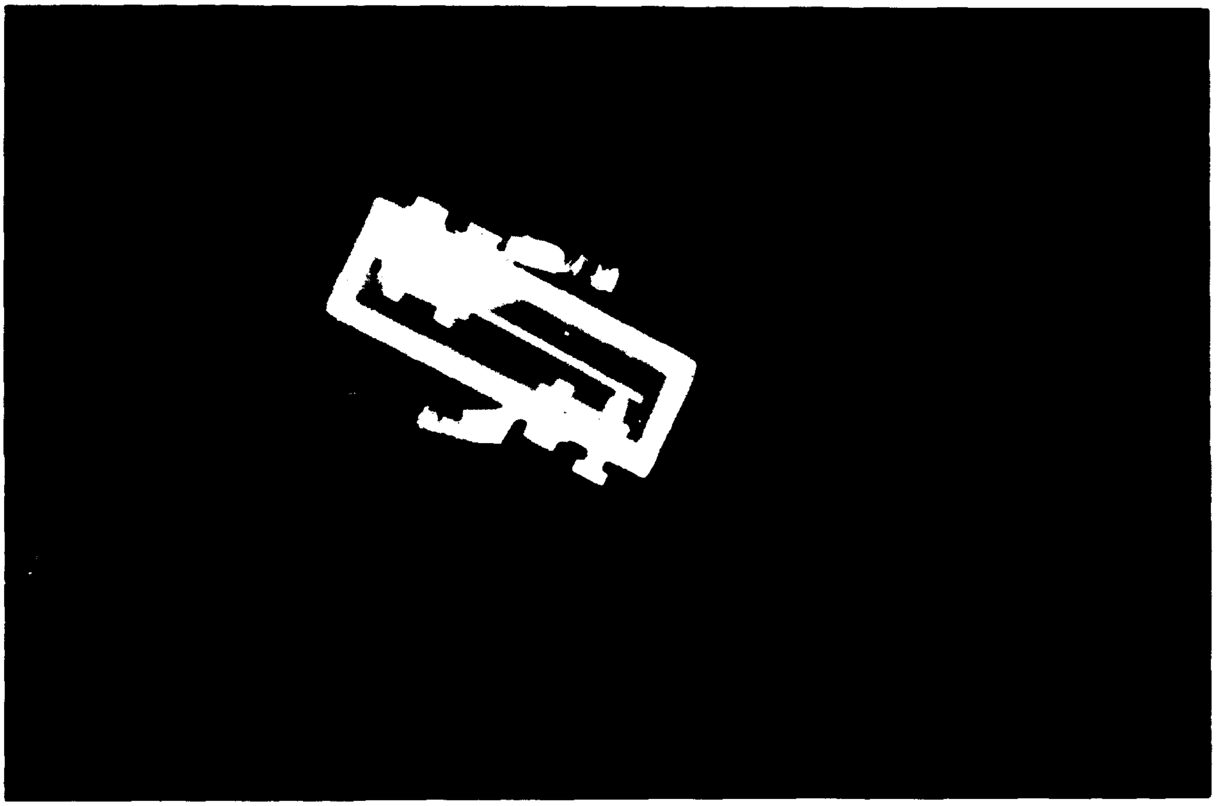

Fig. 121. Radiograph of an electric pad taken at 35 kV.

The position and integrity of the heating element in an electric cooker can be seen in fig. 122 (thickness 9 mm) taken at 50 kV.

12.6. Various applications

Only a few of the numerous applications of paper radiography will be described here.

Fiber-reinforced composite materials can be examined by paper radiography. Work has started on this subject at Risø, where samples of carbon and glass fibers in epoxy matrix are produced and studied by radiography.

Figure 123 shows a radiograph of such samples made of a 3 mm thick carbon-fiber composite, on which different defects can be detected. The radiograph was taken at 12 kV.

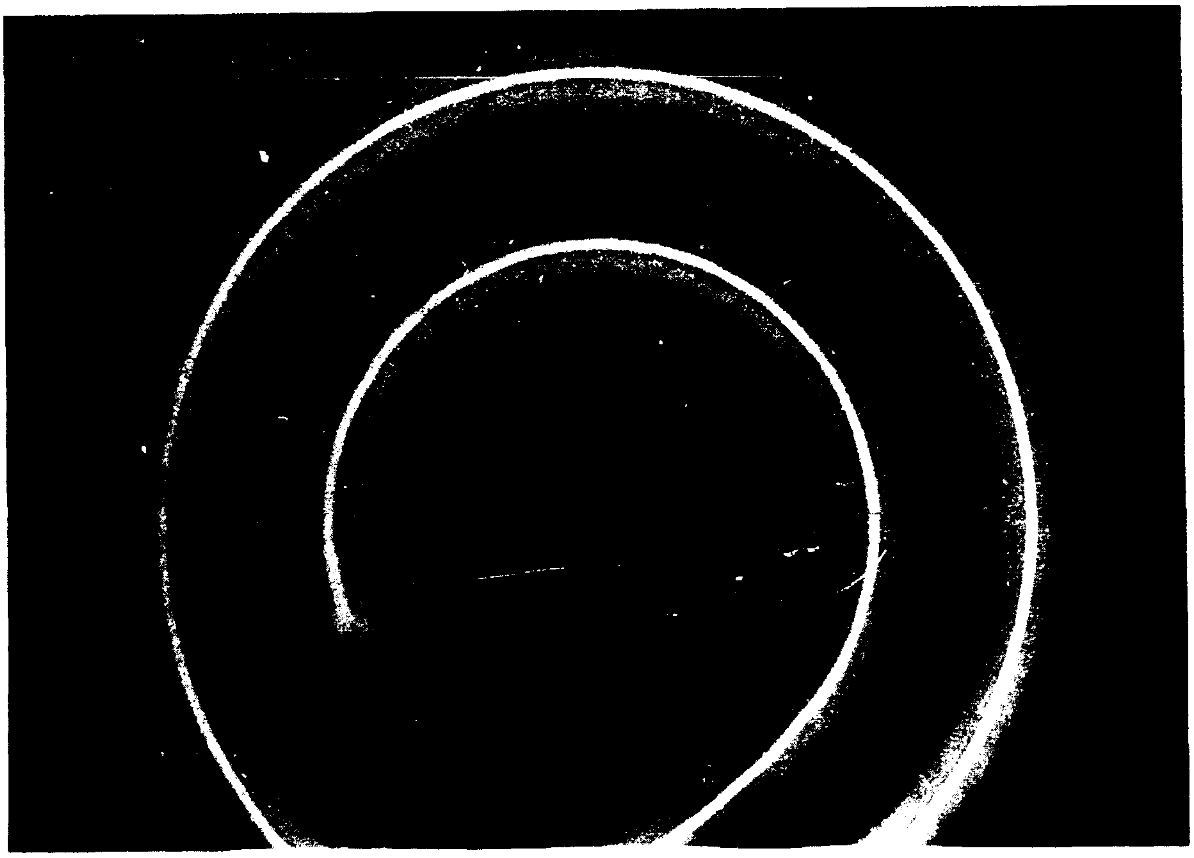

Fig. 122. Radiograph of a heating element of an electric cooker taken at 50 kV.

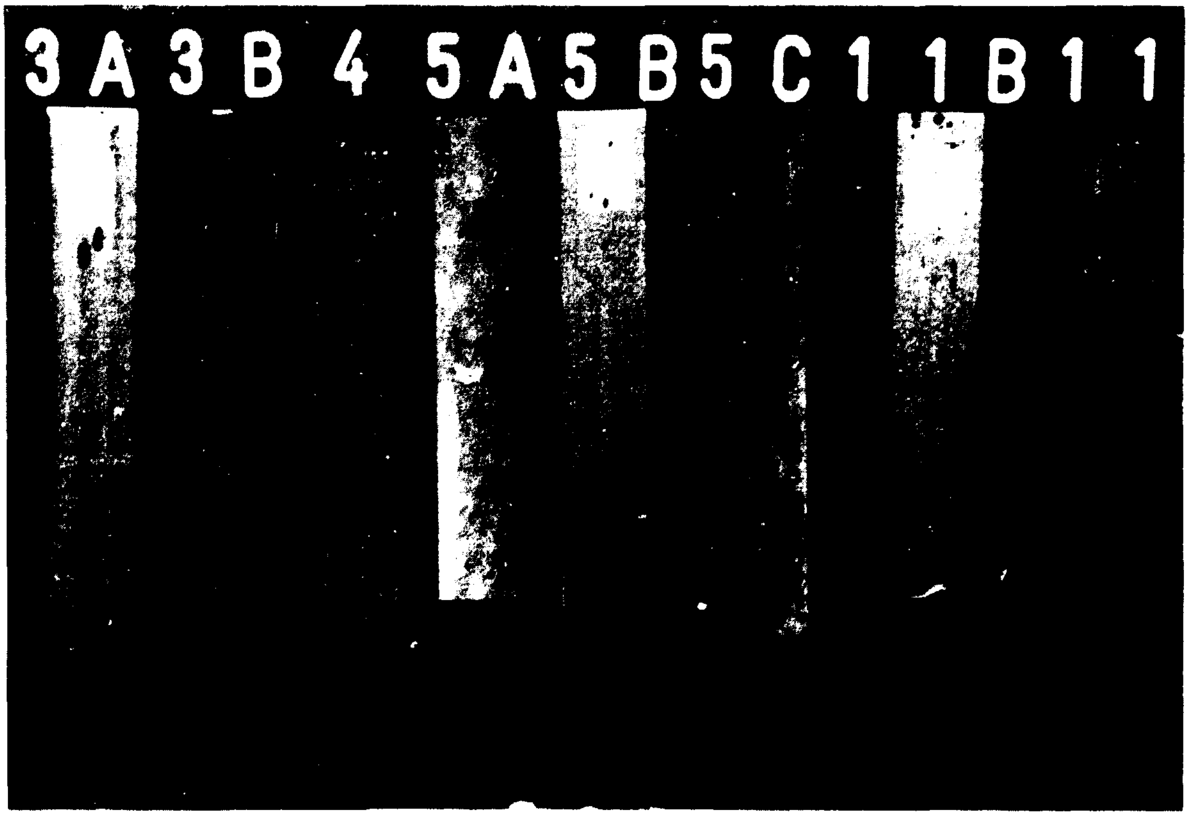

Fig. 123. Radiograph of a 3 mm thick carbon fiber reinforced composite samples taken at 12 kV.

Similar samples were made with glass fibres and fig. 124 shows a radiograph of 3 mm thick samples taken at 20 kV.

Fig. 124. Radiograph of a 3 mm thick glas fiber reinforced composite samples taken at 20 kV.

Paper radiography is very suitable for the control of all kinds of motor vehicle tyre. Figure 125 is a radiograph of a worn 6 x 12 four-ply axial car tyre (22.5 kV), whereas fig. 126 represents a radiograph (30 kV) of a new 195 x 14 radial car tyre. The steel wires in the tyre can be seen on the last picture very clearly.

Fig. 125. Radiograph of a worn 6.0 x 12 axial tyre taken at 22.5 kV.

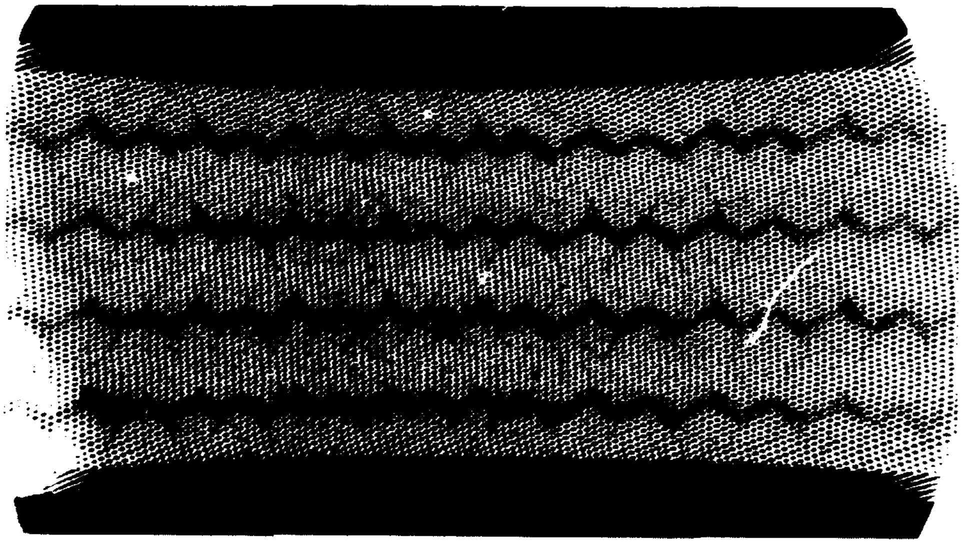

Fig. 126. Radiograph of a new 195 x 14 radial tyre taken at 30 kV.

Low-voltage radiography on paper can also be used outside the technical field, as e.g., in the study of plants. Figure 127 gives a radiograph taken at 30 kV of a giant hogweed flower. Figure 128 reproduces its leaf (taken at 12.5 kV). Another example of plant radiography is a picture of a maple leaf taken at 10 kV (fig. 129) and of a twig (fig. 130) taken at 15 kV.

Fig. 127. Radiograph of a hogweed flower taken at 30 kV.

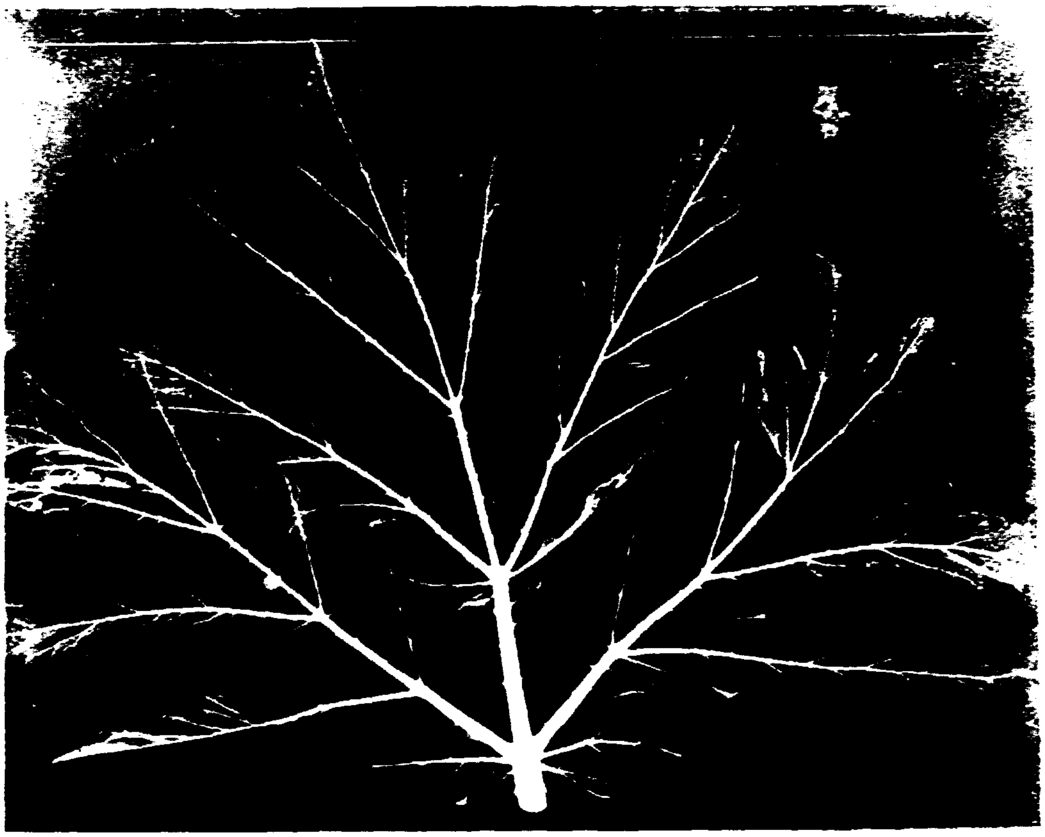

Fig. 128. Radiograph of a hogweed leaf taken at 12.5 kV.

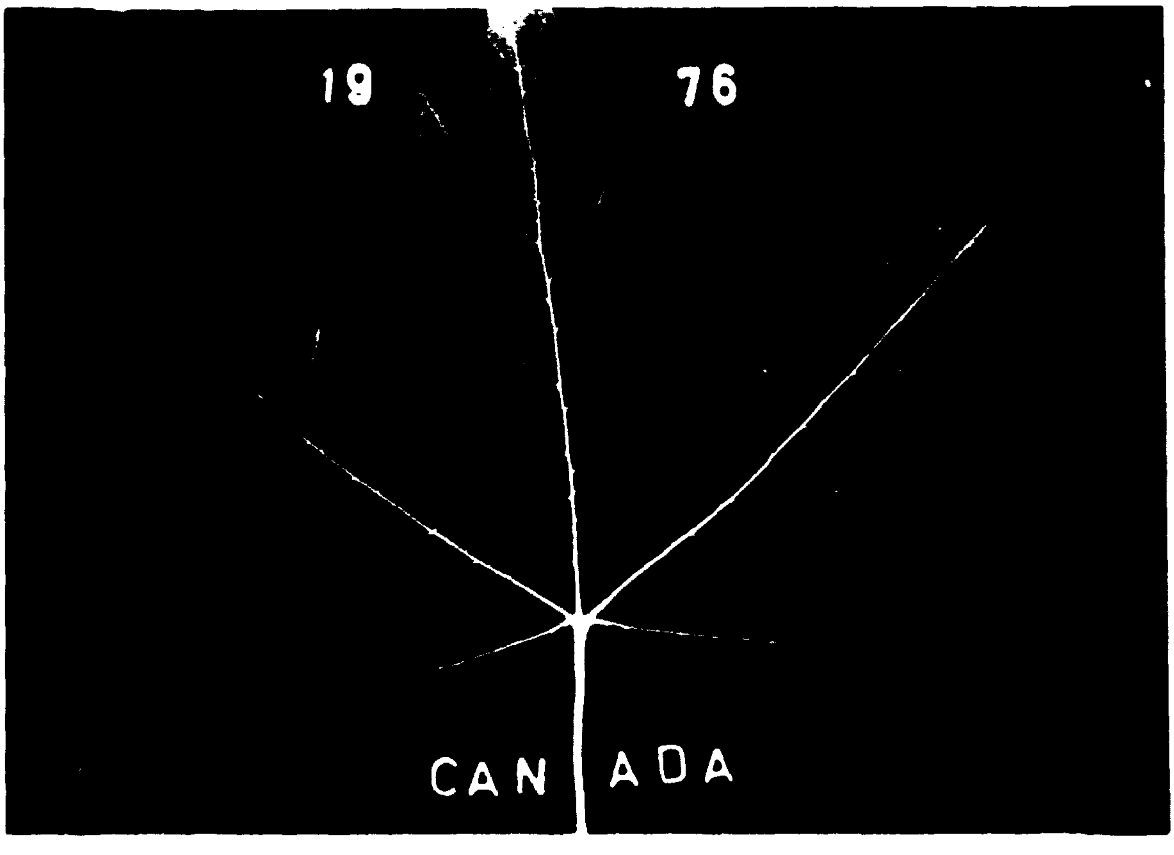

Fig. 129. Radiograph of a maple leaf taken at 10 kV.

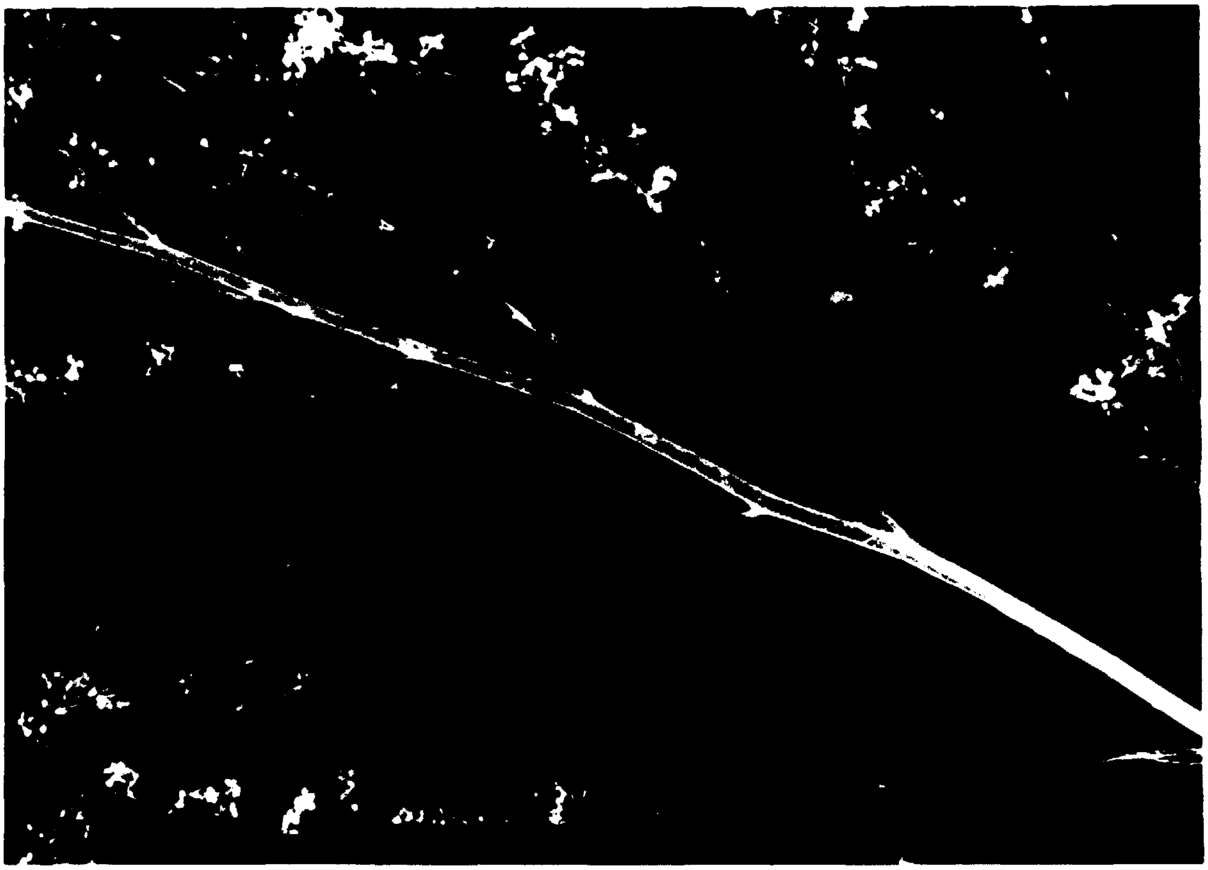

Fig. 130. Radiograph of a twig taken at 15 kV.

13. CONCLUSIONS

From the results of the present investigation as well as from the information obtained during the literature search (see chapter 2 above), the following conclusions can be drawn about the application of radiographic paper in industrial radiography. (Only X-ray radiography was investigated).

13.1. Field of application

Paper radiography can be used to examine the same objects as are controlled by film radiography if a high sensitivity technique is not required. In general, the quality level required by most radiographic standards can be obtained (e.g., the 2-2T level required by ASTM-E142 or the image quality class II required by DIN 54 109).

The best results can be obtained in the low and intermediate voltage range.

For aluminium castings, very good results can be obtained up to 30 mm when using soft X-rays from a beryllium window tube at voltages up to 50 kV (though greater thickness can be also examined, e.g., up to 70 mm with voltages up to 130 kV).

For steel welds, paper radiography can be successfully used with voltages up to 120 kV and thickness up to 12 mm[13)] (or even 150 kV for 20 mm). Steel castings of even larger thicknesses can be examined when high radiographic quality is not required.

Besides these two most important fields of radiography (control of castings and weldings), paper radiography is suitable for the control of various assemblies especially if they are composed of parts with different attenuation coefficients (e.g. metal in plastic, fibers in resins).

Paper radiography cannot be recommended when a high sensitivity technique is required (e.g. thicker steel welds for high pressure vessels).

Paper radiography can also be used successfully for making a preliminary examination, during which the location of a defect can be determined and the correct kilovoltage found, after which the high sensitivity X-ray film technique is used. The above procedure is especially valuable because it considerably shortens the whole control process. Paper radiographs can be obtained ready for use in a far shorter time than film radiographs.

13.2. Equipment

The equipment necessary for the use of radiographic paper is simpler and less expensive than that for film radiography.

The same cassettes can be used with paper as are used with film. Instead of lead intensifying screens, used for most applications of film radiography, fluorescent intensifying screens are necessary for paper radiography (one screen per cassette).

Radiographic paper must be processed in special processors. They are simple in use, have smaller dimensions than film-processing tanks and are cheaper that the later. A water supply is not required and radiographic paper can be processed in about 15 s, whereas hand-processing of X-ray films requires about 1 h (in automatic processors this can be done in about 10 min).

No hangers are required for the processing of radiographic paper as is the case with X-ray film.

The paper itself is about three times cheaper than the X-ray film.

Other accessories, such as IQIs step-wedges or markers, are the same for both paper and film radiography. A reflection densitometer required to read the optical density of the paper costs approximately the same as a transmission densitometer needed for film.

13.3. Sensitometric properties

The speed of radiographic paper, when used with intensifying screens, is very high, especially in the low voltage range.

As can be seen from table 16, at 50 kV the IC and 600 papers are almost 5 times faster than the relatively fast Kodak Industrex D film (or about 10 times faster than the C film). Also in the intermediate voltage range radiographic paper shows much higher speed than the X-ray film (e.g. at 190 kV the IC and 600 papers are about 7.5 times faster then the C film).

At present two paper speeds are practically available: the Agfa-Gevaert Structurix IC and Kodak Industrex 600 (showing almost equal speed) and Kodak 610 (almost twice as slow as the former brands).

Comparing the contrast of X-ray film and paper (table 17,18), one must first observe that the contrast of industrial X-ray film increases constantly with the film density, whereas the contrast of the radiographic paper reaches a maximum (usually at $D_p \approx 1.0$).

The contrast of the X-ray film (measured at $D_f = 2.5$) is higher than the maximum contrast of the paper. The corresponding values for the maximum paper contrast will be between 2 and 3, whereas X-ray films show a contrast (at $D_f \approx 2.5$) twice as high.

Also the exposure latitude of the X-ray film is higher than that of the paper (table 19, 20).

As mentioned before, Agfa-Gevaert offers only one brand of radiographic paper (Structurix IC) and one brand of intensifying screen (Structurix IC type II), whereas Kodak has two brands of paper (Industrex Instant 600, manufactured in the USA, and Industrex 610, manufactured in France). The former is about twice as fast as the latter. There are also two types of intensifying screen marketed by Kodak for radiographic paper: the XO or F1 and the F2, which is slower than the former.

13.4. Quality of the radiographic image

The quality of the radiographic image is usually assessed by the use of image quality indicators (IQI). In the assessment of the radiographs of U/Al blocks and of U/Al plates used in the fabrication of MTR fuel elements, conventional IQI's could not be used. The comparison of the image quality, performed by the methods described in 7.1 and 7.2 above, proved that radiographic paper shows equal quality during the control of MTR fuel plates (table 24) and cast U/Al blocks.

For aluminium and steel, paper radiographs do not show as high a quality as that obtainable with X-ray film (table 25). Usually, one can observe one IQI wire less on paper than on film. Nevertheless, in most cases a 2% IQI sensitivity can be achieved on paper.

13.5. General

As a general conslusion it can be said that radiographic paper is a valuable tool in the field of industrial radiography and it can compete with X-ray film in many fields. It is especially useful when speed and low costs of the radiographic control are required and less radiographic quality can be tolerated.

More detailed information about special fields of application of radiographic paper can be found in 7,8,9,11,12,13,15,23), as well in the few examples given in 12 above.

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